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MECHANICAL ROPE AND CABLE

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An assessment is made of factors including design, materials, environment, wear, maintenance, and fittings that concern mechanical rope. Although ropes have been used for several millenia, the development of rope design and construction has not received much attention. Engineering progress has been hampered by a low rate of information dissemination between designers, manufacturers, users, and maintenance personnel. Conclusions are drawn regarding the need to determine by nondestructive

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evaluation a rope's service life, the extent of internal corrosion, and wear. Rope tests that correlate with service conditions are needed. Among the recommendations are the need for handbooks on mechanical rope engineering, design, and maintenance.

MECHANICAL ROPE AND CABLE

REPORT OF

THE AD HOC COMMITTEE ON

MECHANICAL ROPE AND CABLE

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

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The members of the committee selected to undertake this project and prepare this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. Responsibility for the detailed aspects of this report rests with that committee.

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PREFACE

In conducting its study, the NMAB ad hoc Committee on Mechanical Rope and Cable has benefited from the advice and counsel of scientists and engineers, both in the United States and the United Kingdom, who are experts in this field. Conversations also were held with users of wire rope and wire rope systems and with manufacturers of wire rope and associated hardware. Visits were made to laboratories where wire rope is tested and developed and to shipyards and off-shore drilling and mine sites where it is used.

Comments were solicited from leaders in wire rope research and development (including the now disestablished Battelle Memorial Institute's Long Beach Ocean Engineering Laboratory and the Mechanical Engineering Department of Catholic University of America) regarding the research or related development they considered most needed.

Members of the National Materials Advisory Board study groups serve as individuals contributing their personal knowledge and judgments and not as representatives of any organization in which they are employed or with which they may be associated.

The quantitative data published in this report were intended only to illustrate the scope and substance of information considered in the study and should not be used for any other purpose, such as in specifications or in design, unless so stated.

The Committee wishes to acknowledge the cooperation of the contributors to this study listed below, and especially that of the late Walter J. Kaufman, who served on this Committee until his death and whose intuition and incisive mind conceived and led a program of basic research into previously unexplored aspects of wire rope technology.

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ABSTRACT

An assessment is made of factors including design, materials, environment, wear, maintenance, and fittings that concern mechanical rope. Although ropes have been used for several millenia, the development of rope design and construction has not received much attention. Engineering progress has been hampered by a low rate of information dissemination between designers, manufacturers, users, and maintenance personnel. Conclusions are drawn regarding the need to determine by nondestructive evaluation a rope's service life, the extent of internal corrosion, and wear. Rope tests that correlate with service conditions are needed. Among the recommendations are the need for handbooks on mechanical rope engineering, design, and maintenance.

I. SUMMARY CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Rope* generally is removed from use when visual inspection reveals defects; however, no test or inspection method exists for determining quantitatively remaining rope service life. Most causes of premature mechanical deterioration or damage are well known and preventable.

2. Present testing and inspection procedures are inadequate as monitors of the production and acceptance of rope.

3. Many rope constructions, varying considerably in the manner, size, and arrangement of wires in a strand, as well as in lay arrangement, exist. Although each construction offers special advantages for particular applications, a better understanding of rope behavior is needed to develop more scientific rope design and construction.

4. Internal wire failure, often due to corrosion, is an insidious cause of rope failure and is not detected readily by visual inspection of the rope surface.

5. The effect of stresses, such as tensile, bending, torsion, and compression, upon rope in service is not well correlated.

6. The necessity for and the mechanism of internal rope lubrication are not understood sufficiently.

7. Corrosion is a major consideration in rope manufacture; yet designers, manufacturers, and consumers have not adequately utilized available data on corrosion-resisting materials, and cathodic protection techniques for coatings to prevent or reduce corrosion failures.

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* The term "rope" is used in this report to mean mechanical wire rope and cable.

8. The best mechanical and physical metallurgical techniques may not have been applied to produce the wire in rope manufacture. Plain carbon steel is the material most widely used for such wire because it is most economically effective. However, other materials with better corrosion resistance, better fatigue properties, higher strength, and/or nonmagnetic properties offer advantages for certain applications.

9. Inadequate communication in the wire rope field prevents necessary information dissemination between manufacturers, designers, purchasers, and maintenance people.

10. Present handbooks on the maintenance of rope and rope systems are not sufficiently comprehensive to meet today's needs.

11. U. S. Navy Technical Bulletin No. 5, "Instructions for the Design and Care of Wire Rope Installations," is outdated.

12. Specification RR-W-410C, "Wire Rope and Strand," is too encompassing to meet today's needs adequately and has encouraged a proliferation of ropes that are virtually impossible and extremely costly to stock.

13. Membership in the International Standards Organization Technical Committee 105 (ISO/TC105) might assure obtaining quality rope in emergency overseas procurement, thus reducing excessive shipboard storage and costs, and might promote technology transfer.

B. Recommendations

1. An authoritative engineering handbook should be prepared on the capabilities and design considerations of systems involving rope, fittings, sheaves, and drums.

2. The number of general purpose ropes carried as stock items in the military supply system should be reduced drastically.

3. A current, authoritative maintenance handbook or bulletin should be prepared and issued to replace the existing Technical Bulletin Number 5. This handbook should contain information on rope corrosion resistance and corrosion prevention.

4. A general research program should be initiated (a) to develop tests that simulate service conditions, (b) to determine the fundamental aspects of rope lubrication, particularly as they relate to reducing wear and corrosion and to improving fatigue life, and (c) to evaluate corrosion, lubrication and inspection techniques.

5. Studies should be initiated to improve the understanding of rope cores and their design.

6. Current materials as well as mechanical and physical metallurgical techniques, including corrosion-prevention coatings, should be reviewed to determine how they may be utilized to produce wire for rope. If warranted, experimental rope of new candidate materials or currently used materials that may be improved by controlled metallurgical processing should be fabricated and evaluated.

7. Simple instrumentation should be developed to measure and record in-service data, such as tensile stress and loading frequency, on rope used in critical applications.

8. More precise and reliable inspection criteria should be established for retiring and down-rating rope in various application categories.

9. Specification RR-W-410C should be revised immediately (including a drastic reduction in the number and variety of general purpose ropes) to make it more responsive to Department of Defense needs.

10. Membership in the ISO-TC105 as a participating member is recommended to keep abreast of European rope development and for obtaining quality rope in overseas procurement.

11. A wire rope information center should be established to collect, coordinate, and disseminate data (particularly on corrosion prevention) and improve information transfer.

II. INTRODUCTION

A. Purpose and Scope

This study was undertaken by the National Materials Advisory Board ad hoc Committee on Mechanical Rope and Cable at the request of its sponsor, the Department of Defense. The Committee's charge was to study the technical problems encountered by the military services in the use of mechanical rope and cable and to recommend appropriate programs, including research and development, for their solution.

Considerable confusion exists regarding the precise meaning of the terms "cable" and "rope." Rope is defined in this study as a built-up flexible structural member designed for tensile capacity regardless of the application and excluding single-element construction (i.e., rods and/or single wires). The Committee, with the concurrence of its sponsors, chose to consider only metallic wire rope and to restrict itself to use of the terms "wire rope" or "rope." Thus, the term "cable" will not be used in the remainder of this report.

B. Background

Ropes, in something like their present configurations, have been used normally in the transfer of tensile loads since the days of the Roman Empire. Since that time, exceptionally adaptable manufacturing equipment has been developed and a vast array of rope constructions made available for a variety of applications. Despite centuries of practical experience in making and using rope, its prosaism has not attracted serious scientific and engineering attention to the product, the system involved, or their misuse--a lack often manifested by in-service rope failures resulting in loss of lives and expensive equipment.

To complicate matters, no reliable techniques are available for determing when to retire an in-service rope before it fails. In addition, during the past decade, the rope uses, especially in the U.S. Navy (USN), have become so diverse, sophisticated, and costly that the guidelines and criteria established for yesterday's systems, system operation, and maintenance cannot be used with confidence in today's applications.

C. Current Situation

Sophisticated USN operations (including deep-sea mooring, at-sea replenishment, salvage operations, shipboard handling of submersible vehicles, and accurate emplantment of systems in sea floor construction) utilize rope. These applications require a better understanding of involved failure mechanisms when ropes are used to transfer mechanical loads in a marine environment. (See Appendix A for a discussion of Navy wire rope usage and related problems.)

The U.S. Army (USA) also employs rope for a variety of uses in construction, elevators, construction equipment, towing of land vehicles, fuel handling equipment, ship-to-shore launch items, aircraft control cables, and helicopter cargo handling systems. Many of these applications and problems are similar to those of industry. Nevertheless, the Army does encounter some unique rope problems, primarily in aircraft applications. (See Appendix B for a discussion of Army wire rope usage and related problems.)

Rope problems of the U.S. Air Force (USAF) are not as severe as those experienced in Naval applications. However, all the Services have a serious short-life problem with high-strength, small-diameter antenna rope and no reliable methodology for nondestructive evaluation (NDE) of rope. This lack of NDE capability necessitates conservative replacement practices that increase the overall operating costs of USAF systems. (See Appendix C for a discussion of Air Force rope usage and related problems.)

In the mining industry, rope usage has been standardized by incorporating good engineering practice into federal and state regulations. In critical applications involving hoisting people, such as ropes for hoisting shaft cars and aerial tramways, federal and state regulations control the selection, usage, inspection, and retirement of rope. As problems arise, they are referred to the rope manufacturers for analysis and solution. (See Appendix D for a discussion of wire rope in the mining industry.)

While it is recognized that a better understanding of wire rope is needed to solve current problems, previous research programs were fragmented and focused only on specific problems. Some of this research produced very useful information; however, the developed data were not disseminated widely and are not used fully by the designers or users of today's wire rope systems. Moreover, in many cases, the data are inadequate for use in upgrading existing design specifications, standards, and manuals.

III. DESIGN AND ANALYSIS

A rope is a complex mechanical/structural system with many interacting components. Design and/or analysis must consider a variety of factors, singly or in combinations. These factors may include tensile load, bend radius, crushing load, bearing pressure, dynamic conditions, fatigue, rotational limitation, obtrusion, corrosion, wear, environmental conditions, and fittings and sheaves. Therefore, the remainder of this section should be considered within this context of wide variations in geometrical design and operational requirements.

A. Design Geometry

The term "design geometry" applies to the configuration in which a rope is manufactured. Of direct interest are the manufacturing process, the approaches used, and the limitations implicit in these approaches. Accordingly, it is useful to start with a simple description of the rope elements and construction. Rope is a product made of many moving parts, each of which must be free to move in relation to the others, particularly if the rope is designed to move over sheaves and wind onto drums. A rope is made up of three components--wires, strands, and cores. The smallest component, the basic element, is the individual <u>wire</u>. A number of these wires are laid in a definite geometric pattern around a single wire, called a center wire, to make a <u>strand</u>. Finally, a number of strands, usually six, are laid around a <u>core</u> to make a rope.

The core upon which a rope is constructed is vitally important to its mechanical properties and service life; some ropes are built upon independent wire rope cores (IWRC), while others employ synthetic or natural fiber cores. Some individuals believe that the fiber core serves principally to retain an oil lubricant to prolong wire rope life (NMAB-298, 1972),* while others feel that the

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* This report discussed fiber as cores to wire rope only briefly inasmuch as only a small percentage of cordage was used for this important purpose. The report recommended further research and development on the usability of synthetic fibers for this application.

core only serves to support the strands of rope. Research and development are necessary on the function of the fiber core in wire rope so that the optimum material may be used.

It is useful to consider these components individually. The great majority of wires used are round but, for a few very special purposes, shaped wires (e.g., flat, Z- or H-shaped) may be used. To date, the most economically effective material for wires for operating wire rope is cold-drawn, plain carbon steel; a number of alloy steels have been tried but their application has been limited. Most wire is uncoated, but, for some purposes, coatings (e.g., zinc and aluminum) are applied to the wire either before or after the final wire-drawing process. The wires in a strand, usually of various sizes, are laid up* helically in a predetermined pattern around a center wire. The number of wires and their geometric arrangement is called the "construction" of the strand, and the wires, strands, and cores may be fabricated in a wide combination of cable constructions. Thus, rope is not simply a number of wires, strands, and a core twisted together; actually, it is engineered carefully and the components (wires, strands, and core) are laid together in a prearranged and engineered pattern to fit in a proper designed position.

Excluding corrosion, rope life normally is determined by fatigue and wear (abrasion). An operating rope is bent continually over sheaves and wound onto drums. While a small-diameter wire usually will stand more bends around a given pulley or sheave than a larger-diameter wire, repeated bending eventually

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* The term "lay" has two meanings: (1) it designates the longitudinal length a wire takes to move once around a strand or a strand around the rope, and (2) it refers to the direction the wires and strand spiral the rope. In this latter context, the terms "right lay" and "left lay" are used to designate the direction of the spiral of the rope. If the wires rotate in a direction opposite to the direction of the strands, the rope is called a "regular lay" rope; if the wires rotate in the same direction as the strand, the rope is called a "lang lay" rope. There are specific uses for right lay and left lay as well as for regular and lang lay wire ropes.

will break any wire. Generally, abrasion of rope for a mine slope or a dragline excavator is resisted most successfully by using larger-diameter outside wires in the strand design. The above factors are completely different in their effects, and a compromise usually is made in the design and application of a rope for any specific operating duty. Lubrication of rope during manufacture and use is important.

Many rope constructions are available--some suitable only for a single or very few purposes and others suitable in differing degrees for a wide variety of applications. There are many special-purpose applications for which existing rope designs are not optimum and for which new designs are feasible and warranted.

In general, rope manufacturing problems per se may not warrant a research program. While rope manufacturers must know the limitations of, and make modifications to, their machinery to allow satisfactory production of the designs, these are straightforward engineering problems as are those of rope construction design. Constructional stability may be a problem in a new rope construction that is widely different from anything previously made and may require an empirical solution, the traditional fashion for solving rope constructional stability problems.

Although design and engineering apparently are adequate for the majority of today's applications, research on new rope concepts should be initiated to stimulate improvements in rope construction, performance, and maintenance.

B. Stress Analysis

Ropes subjected to static and dynamic loads experience macroscopic and microscopic stresses. Obtaining data on the stresses at all points within a rope during its life, and evaluating factors such as load history, environment, and local failure, are desirable, but current knowledge is insufficient to permit such information gathering and evaluation. Various techniques, however, are available for assessing the stress characteristics of wire rope, and these will be discussed briefly below.

1. Full-Scale Testing

Full-scale testing includes actual field usage of rope. With certain limited exceptions (e.g., mine hoist ropes and elevator cables), at best, field experience provides crude data on service loads or rope life because the variables are numerous and ill defined. However, it has led to the development of factors of safety applicable to tensile loads for normal rope constructions and for conventional usage.

Considerably more information can be gained from full-scale testing under controlled (laboratory) conditions. Several significant facilities are available but, to date, primary attention has been devoted to special applications. Since full-scale testing requires considerable time and effort to obtain data on a single rope size and construction, accumulation of test results is a slow process. Also, there is no direct correlation between full-scale laboratory testing and field usage. Nonetheless, full-scale testing is valuable and should be continued to provide check points for comparative approaches that are less elaborate and expensive.

The testing of full-scale components of rope and strands is used extensively in normal qualification and acceptance testing and is a distinct advantage. Often, component testing has been an arbitrary procedure for measuring material or component behavior. Such tests are of limited interest here. For stress analysis purposes, a component test is useful only if the test simulates the actual conditions within the rope and the behavior of the component within the rope. Several component tests have been designed that relate to actual usage.

2. Scale-Model Testing

Scale-model rope tests are a useful, low-cost tool for simple testing. This general approach can be used in conjunction with available full-scale data to establish empirical relationships of substantial usefulness. At present, however, scale-model testing is limited by the lack of a fundamental understanding of rope behavior.

3. Experimental Stress Analysis

A wide variety of tools and techniques is available for experimental stress analysis. The least sophisticated of these techniques (e.g., load cell, strain gages) commonly are used on rope; to date, the more sophisticated approaches (e.g., photoelasticity and holography) are of limited value because of the complex nature and interaction of rope components. Experimental techniques using simulated materials are helpful only in establishing initial stress conditions or in obtaining experimental data for the simulated material.

Experimental stress analysis techniques are most applicable to local problems (e.g., the stress state at the point of contact between individual wires within a strand) and are standard procedures that should be used more extensively for measuring loads, stresses, and strains. Because of material simulation limitations, more sophisticated experimental techniques are used primarily to provide experimental test points against which to test a theoretical approach. However, once verified, the theoretical approach can be applied with greater confidence.

4. Strength-of-Material Approaches

Such approaches have been applied to rope with noticeable success because they are relatively simple and available experimental data can be introduced easily as empirical coefficients. When empirical coefficients are introduced, the equation utilizing them may have limited applicability, and such an analytical method depends upon having considerable experimental data available on a rope of similar construction and size to the one of specific interest. This approach is used to reduce the experiments that are needed to obtain the required information and serves as a planning technique for developmental work on new rope or materials. More extensive use of analyses for this latter purpose is to be encouraged.

5. Analytical Stress Analysis

Over the past decade, analytical stress analysis has developed greatly, based primarily on computer availability and capacity. Finite element and/or finite difference techniques can be applied routinely to problems that were impractical to solve only a few years ago. These techniques handle complexities of material characterization, geometry, and component interaction similar to those found in rope. Application of these techniques to rope should improve understanding and help guide development and experimental work.

Over the years, some excellent researchers became interested in stress analysis of rope, but because of the modest financial support, their work has been spotty and mostly on short-term projects. Since rope always will be used, the need for understanding rope behavior and a program to develop the required knowledge is obvious.

6. Design Publications

Very little design information of specific value to a potential rope user was found in available specifications, handbooks, and other publications. For example, the U.S. Navy's Technical Bulletin No. 5, the guide for military users, is outdated and incomplete. In addition, while considerable information of varying usefulness is available on specific aspects of rope technology and considerable research has been done, the lack of an appropriate medium (no technical society has a particular interest in the specialty) for publishing rope information has kept this knowledge out of the mainstream.

C. Conclusions and Recommendations

1. Conclusions

a. Many rope constructions exist that vary considerable in the number, size, and arrangement of wires in the strand, as well as in lay arrangements. Although certain constructions offer special advantages for particular applications, a better understanding of rope behavior is needed to reduce empiricism in design.

b. The considerable literature on rope contains little design information of value to a potential user.

c. The actual tensile stress, fatigue conditions, and radial bearing pressures imposed upon rope in service generally are not determined readily and the few systems available for measuring these parameters are of questionable value.

d. The effect of stresses, such as tensile, bending, torsion, and compressive contact, on rope is not understood well.

2. Recommendations

a. A program to develop a better understanding of rope behavior should be initiated. Such a program should include:

(1) A long-term plan and commitment.
(2) Strong government lead (individual and group).
(3) A minimum of three significant sponsored research groups.
(4) Periodic symposia for the presentation of research results relating to rope (U.S. industry and foreign technology also should be invited and involved).
(5) A system for encouraging information dissemination outside of the rope community.

At least several years (perhaps five years for a significant improvement in the understanding of rope) would be required for such an activity to become productive. For several additional years, the annual effort probably would produce results of significant value. Beyond that, however, government support could cease or, perhaps, be limited to sponsorship of an annual symposium.

b. A research project to develop, evaluate, and recommend a variety of alternate rope concepts should be initiated and conducted by an organization uncommitted to current rope concepts.

c. A nonlinear finite element analysis should be developed that will reproduce the stress state in rope under static, dynamic, and environmental conditions. Considerably more attention should be devoted to stress analysis in general. The finite element analysis is an approach that appears to offer new understanding.

d. A project to prepare a wire rope engineering handbook should be initiated. The handbook should include tables covering such aspects as sizes, minimum mechanical properties, corresponding sheave sizes and fittings, and relative corrosion-fatigue strength in rope-use environments to aid in the selection of ropes and fittings. Also, the handbook should include detailed information on the rope construction, the engineering and sizing of sheaves and applicable systems elements, lubrication and maintenance, inspection, and the systems' design implications of the rope use. The handbook should be quantified so that a designer can optimize the rope selection for particular service requirements.

IV. FITTINGS AND SHEAVES

Fittings transmit the load between the tension member (rope) and some other fixture. Also, fitting design must be compatible in dimension and strength with the rope. The drum of a winch or other machinery to which a running rope is attached and wound may be considered a fitting. Capstan heads and the shoes of traction winches, while not actually holding the end of the rope, often are considered as fittings in the same sense as the winch drum. Some traction winches are basically large sheaves in series.

Some manufacturers of rope also manufacture fittings. Sheaves, with the exception of applications such as an equalizing bridle, are associated almost exclusively with the ultimate system or employment of the rope. Generally, sheaves are not supplied by the rope manufacturer.

A. Design

The treatment of rope fittings/sheaves in recognized engineering handbooks or design data sheets is as meager as that of rope; little data are available in other than rope manufacturers' catalogs and handbooks.

Rope manufacturers' sales engineers are familiar with the capabilities and design of most types of fittings/sheaves and can advise their customers. Nevertheless, major misconceptions exist among rope users, and poor design practices are frequent in applying fittings to ropes or in running/operational systems. Examples of poor practice include (1) undercapacity sheaves, and (2) assuming end fittings (such as the patented wedge socket) at 100 percent design efficiency rather than the accepted 70 to 90 percent given in various wire rope manufacturers' handbooks.

Sheaves are understood even less than fittings and often are designed improperly. While information is available in rope manufacturers' handbooks (ARMCO, 1972) and others (USN, 1946; API, 1972), these data are conflicting and incomplete.

Additionally, the system designer tends to employ the smallest possible sheave and drum sizes in order to reduce the dimensions of a particular system, contending that the rope manufacturers' recommended formula for determining sheave or drum size (D/d ratio)* favors the rope. This situation is complicated further by drum applications where the rope is wound in three or more layers, a situation requiring even more generous D/d ratios. Such decisions reduce the system's factor of safety and operating life. Little information is available on the trade-off degradation in design factor of safety or system life cycle which may result from too small D/d ratios.

In short, no authoritative or satisfactory rope systems engineering handbook is available for designing even simple, routine ocean engineering/ rigging systems. Also, Navy Design Data Sheets are unavailable for designing rigging systems for shipboard or ocean engineering applications (a particularly critical lack when man-rated systems, such as those for handling diving capsules and submersible vehicles, are concerned). In addition, no known general standards have been issued in this area by either the American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), or International Standards Organization (ISO).

B. Conclusion and Recommendation

1. Conclusion

Very little testing or development work is underway on fittings and sheaves, and few design standards exist in this area.

2. Recommendation

An authoritative engineering handbook is recommended to deal with the capabilities and design considerations of systems involving wire rope fittings, sheaves, and drums.

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* D/d = diameter of sheave or drum/diameter of the rope.

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V. MATERIALS ASPECT

The materials aspect of wire rope is complex and closely related to all phases of rope manufacturing. Over the years, guidelines were developed by manufacturers and users that attain the optimum configuration and rope life for a variety of materials and uses. No "best" combination of materials and design exists for all ropes. An optimum rope for a particular application is produced by a thorough understanding of the rope properties required for that application and an ability to assess the importance of these factors.

Presumably, if a basic understanding of the relationship between rope properties and the materials and configurational aspects is developed, the design of special rope should not be difficult.

A. Designations and Mechanical Properties

The standard wire rope materials are a series of plain carbon steels identified as iron, traction steel, mild plow (MP) steel, plow (P) steel, improved plow (IP) steel, extra improved plow (EIP) steel, and, more recently, double extra improved plow (DEIP) steel (AISI, 1973). These designations only indicate the breaking strength and do not describe the wire's structure or composition. Moreover, only two properties, the breaking strength and the number of torsions*, normally appear to be measured (AISI, 1973). Furthermore, these designations are not absolute and have an empirical size dependency (Figures 1 and 2). Since the normal rope wire practice is patenting** combined with cold-drawing, the

*Torsions are the number of 360 degree twists a fixed gage length (generally 8 inches) of wire can undergo before failure, and are used as a measure of ductility.

**This is a heat treatment in wire making, applied to medium or high carbon steel before the drawing of wire or between section-reducing drafts. This process involves heating to a temperature above the transformation range, and then cooling in air or in a bath of molten lead or salt to a temperature below that range appropriate for the carbon content of the steel and to the properties required of the finished product (presumably, to produce a fine pearlitic structure.

size dependency of the required properties appears to reflect the decrease in hardenability of plain carbon steels with increasing wire size using present processing techniques (Bethlehem, 1973).

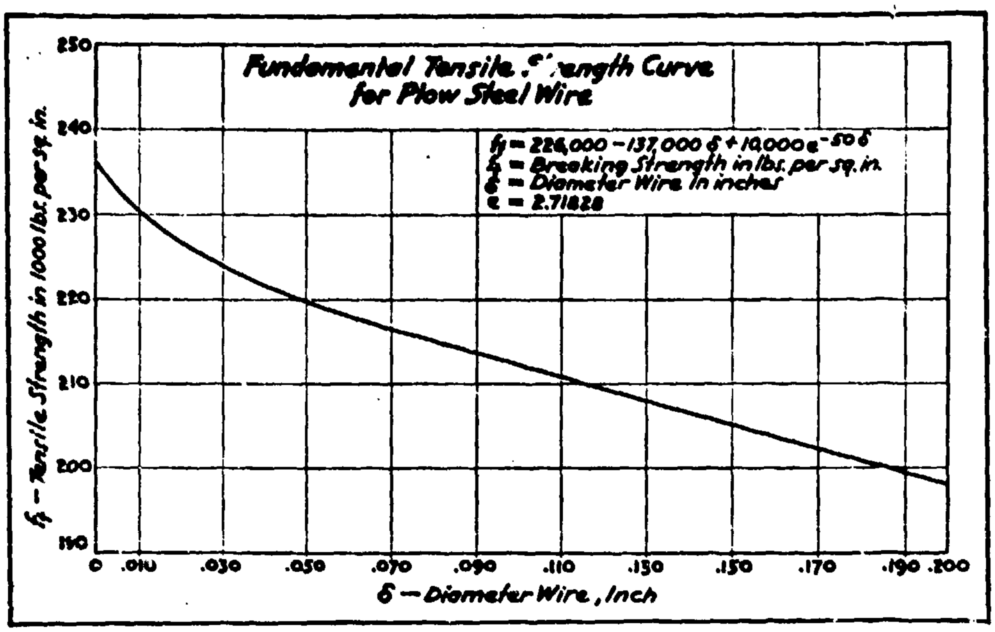


FIGURE 1. Fundamental Tensile Strength Curve for Plow Steel Wire (The American Iron and Steel Institute, 1973).

The curves in Figure 2 show that the strength level of any particular grade of steel at a diameter of 0.010 inch is approximately the lowest strength of the next higher grade at a diameter of 0.200 inch. Also, the required number of torsions are both size- and strength-level dependent. In addition, for EIP steel, the number of torsions required for galvanized steel is somewhat less than that required for bright (uncoated) steel of the same size.

At present, ordinary steel rope wire is specified generally by strength level and a special measure of ductility. One of the primary reasons for this is that rope construction is defined essentially by rope industry standards. A proprietary processing technique for improving the other properties of the rope wire is one of the few mechanisms that a producer has to develop a competitive edge.

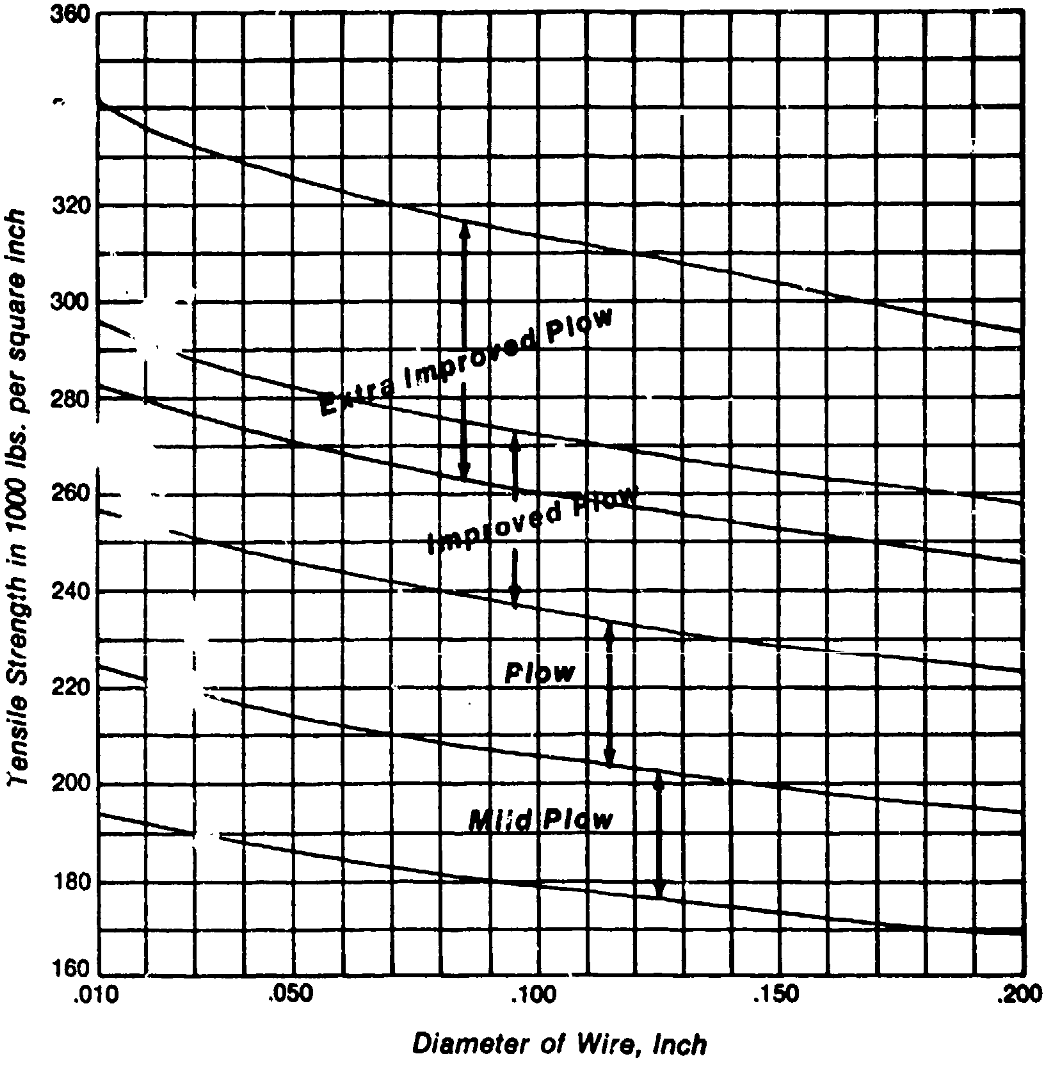


FIGURE 2. Tensile Strength Limits for Indicated Rope Wire Grades (The American Iron and Steel Institute, 1973).

Rope also is formed from materials other than carbon steels (e.g., bronze or stainless steel) and such rope has similar specifications. Special property requirements are negotiated by the customer with the wire rope manufacturer on an individual basis.

The processing of the wire itself, especially the drawing operation, controls the development of microstructural damage, residual stresses, crystallographic texture, and surface conditions in the wire product prior to utilization for rope. Changes in the wire drawing parameters (such as die configuration, reduction per pass, lubrication, and temperature) can alter these material properties. Frequently, the surface residual stresses resulting from wire drawing are tensile and may magnify problems involving stress corrosion; however, these residual stresses may be relieved by plastic deformation of the wire during service. Little information is available on the nature and magnitude of the residual stresses in rope wire as a function of usage. The crystallographic textural changes resulting from processing variations appear minor, but significant differences, both in surface condition and internal structural damage, are observed when the process variables are altered.

B. Service Life Considerations

Based on experience, the major factors limiting the life of wire ropes are fatigue, abrasion, overloading, corrosion, and crushing. Mishandling, such as kinking and bird-caging, seriously shortens rope life but is not considered normal wire rope usage. With respect to any material from which wire rope is fabricated, the properties that control its utility and life expectancy are tensile strength, ductility, wear resistance, and fracture toughness. Corrosion resistance is also extremely important (see Chapter VI). Strength is a function of material, construction, and rope size and is measured easily. However, a specific correlation is not easily found between the ultimate strength of wire and the tensile strength of the wire rope in each of the various configurations.

A study of the mechanical behavior of rope has shown that even the definition of failure may be ambiguous when applied to the complex cable system (Laura et al., 1970). A "first failure load," defined as the maximum load reached, was measured during tension tests of cable. At this point, some strands in the rope still were intact so that a configurational reorientation occurred, apparently unloading the machine. Continued stretching produced a "second failure load," at which point the majority of the remaining strands and core broke, although the failure was not always complete even then. This load, a minor fraction of the first failure load, depended on the number of strands that did not fail initially. The major observation of this limited study was that, with the same rope geometry, traction steel had the lowest load-carrying capacity of the steels studied, but its reserve strength (second failure load) was greater than that of EIP steel and an undefined stainless steel. Also, the EIP steel had essentially the same initial strength as the bright IP steel rope in the 6 x 19 construction (the only one comparatively tested). Presumably, the wire strengths for any given construction were the same.

Aside from corrosion, the principal rope service problems are fatigue failures in various forms. Usually, fatigue failures develop slowly, beginning relatively early in the life of certain wire rope constructions (e.g., the IWRC). A limited reduction in future life expectancy is tolerated. The major concern is determining when the progression of failure is so rapid that total failure is imminent.

Undoubtedly, in general rope utilization, the repeated flexing of rope in running over sheaves and winding on drums under load, is the major cause of fagigue failure. Only in such cases as the towing of a ship in a seaway or in a ship-to-ship underway replenishment, may a cyclic direct tension loading occur. Because of the complexity of the rope structure, the rope may survive several strand failures before it finally snaps.

Fatigue failure of materials occurs in a progressive mode stemming from cyclic stressing, and the rate of failure is dictated by the nature and magnitude of the stress cycle and the operating environment. In high-cycle fatigue, failure occurs by the development of a crack at a local site in the body where the bulk of the solid is only elastically stressed. High-cycle fatigue means that failure occurs after millions of load cycles. Although the boundary between low- and high-cycle fatigue is not clearly defined, low-cycle fatigue results when the entire cross section under load is strained plastically. Under these conditions, generally, fatigue life is less than tens of thousands of cycles. The ability to resist fatigue failure should be an important consideration when choosing characteristics desired in rope materials.

The problem that arises when rope traverses a sheave or drum may be ·strated by an oversimplified analysis. The deformation of the rope, as it conforms (in bending) to the drum or tread diameter of the sheave during operation. is strain-controlled, not stress-controlled as in tensile loading. The maximum tensile strain, ϵ, is at the outer surface of the bend. A comparable compressive strain exists at the inside surface of the bend. Table 1 shows that for 6 x 7 wire rope under the severest fatigue conditions, the smallest recommended ratio of sheave diameter to rope diameter is 72:1. The 6 x 7 rope construction has the greatest susceptibility to fatigue because it has the greatest stiffness.

For the bending aspect of the problem, no difference in modulus exists from steel to steel, nor is the ultimate tensile strength important except that the yield stress is related loosely to the tensile strength. When the tensile load is 25 percent of breaking strength, the "bend-over-sheaves" life is approximately 10,000 cycles while the axial load life for the same wire rope is between 200,000 and 1,000,000 cycles (a 95 percent to 99 percent reduction in fatigue life) (Reemsnyder, 1972).

TABLE 1. Sheave-Diameter Factors (The American Petroleum Institute, 1972; data taken from a portion of Table 3.1).

Rope Classification	Sheave Diameter Factor, F†	
	Condition A*	Condition B**
6 x 7	72	42
6 x 17 Seale	56	37
6 x 19 Seale	51	34
6 x 21 Filler Wire	45	30
6 x 25 Filler Wire	41	27
6 x 31	38	25
6 x 37	27	18
8 x 19 Seale	36	24
8 x 19 Warrington	31	21
18 x 7	51	36

† Sheave Diameter Factor $= \frac{\text{Sheave Diameter}}{\text{Rope Diameter}}$.

* Condition A - Where bending over sheaves is of major importance, sheaves at least as large as those determined by factors under Condition A are recommended.

** Condition B - Where bending over sheaves is important, but some sacrifice in rope life is acceptable to achieve portability, reduction in weight, economy of design, etc., sheaves at least as large as those determined by factors under Condition B are recommended.

The fact that the service failure of wire rope operating over sheaves is a form of low-cycle fatigue is substantiated further by the data in Figure 3 (American Petroleum Institute, 1972). The equation for the curve presented is of the form:

$$L = \frac{R^2}{38} - 2,$$

where L = bending life over sheaves and $R = \frac{D_T}{d}$ (sheave tread diameter/rope diameter). Since bending around a sheave or drum produces strain-controlled deformation as stated previously, this equation can be shown to have the same form as that developed by Coffin for strain-controlled low-cycle fatigue. Remembering that

$$\epsilon = \frac{d}{D_T} = \frac{1}{R},$$

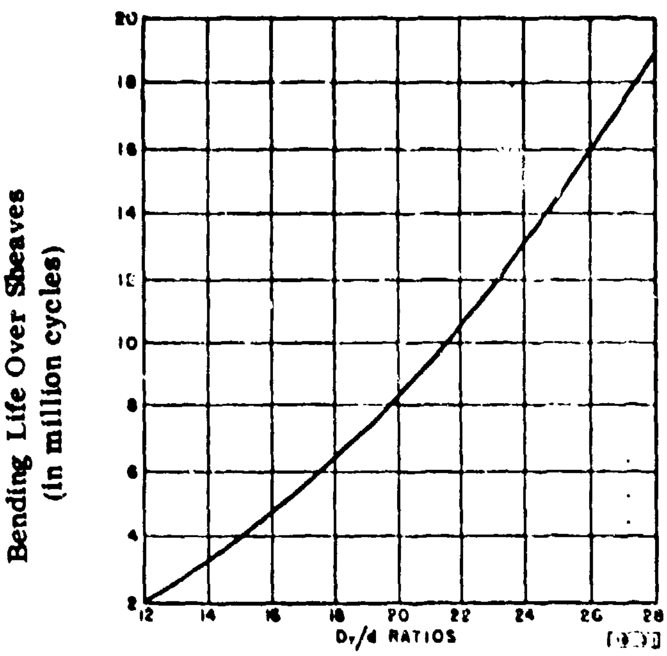
this equation is:

$$N^{1/2} \quad \Delta \epsilon = \text{Constant},$$

where N = number of cycles to failure and $\Delta \epsilon$ = strain range.

When the rope has an independent wire rope core (IWRC), the core is fractured completely after about one percent of the fatigue life (Reemsnyder, 1968). This fact indicates that a main function of the IWRC is as a non-crushable core for the outer strands, and that the rope survives severe loading conditions for any extended period only as the result of configurational changes of the wires and outer strands under load. Obviously, rope is a complex structure <u>whose geometry varies during its service life</u>.

Another material problem in wire rope usage, and sometimes a cause of deterioration, is the formation of brittle martensite in the outer layers of the surface wires resulting from rubbing at high speed (Trent, 1941). It is the major problem encountered in aircraft carrier arresting systems where a landing gear arresting hook engages an arresting rope to stop the forward motion of landing aircraft.



D_T = tread diameter of sheave, inches

d = nominal rope diameter, inches.

FIGURE 3. Relative Service for Various D_T/d Ratios for Sheaves — Based on Laboratory Tests Involving Systems Consisting of Sheaves Only (The American Petroleum Institute, 1972; data taken from Figure 3.1).

The martensite results from the adiabatic heating of the surface caused by high-speed friction and plastic flow followed by a subsequent rapid cooling (quench). If the eutectoid temperature is exceeded, the steel's microstructure is converted to austenite. When the localized heat generation ceases, the still cold remainder of the steel wire rapidly quenches the hot surface to produce martensite. The higher the carbon content of the steel, the harder and more brittle is this martensitic structure. The carbide structure of the fine pearlite in the patented steel wire used in wire rope is very susceptible to this double transformation. However, alloy steels are available that do not transform to austenite on heating. Also, other means of strengthening iron may be less likely to form brittle martensites during such a thermal cycle.

Abrasion occurs extensively in wire rope applications, such as a dragline excavator rope and a mine slope rope. The approach to the problem of outside wire wear has been to adjust the wire rope configuration for the job rather than altering the material properties. By design, the outer wires of each strand are made relatively coarse, providing a margin for material loss prior to wire separation or breakage.

Currently, materials or material processing technology are not obvious solutions to the abrasion problem, since the various methods of improving wear resistance by increasing hardness (e.g., quenching followed by a low-temperature temper, case hardening, or nitriding) produce less tough material and probably increase fatigue and brittle fractures. One possible alternative is to use materials that transform under strain (e.g., the Hadfield manganese steels to high hardness and the relatively new Transformation Induced Plasticity [TRIP] steels at lower hardnesses). In general, when extensive abrasion is inherent in an application, a modification of wire rope construction or materials is a partial solution because the modus operandi cannot be altered. Empirically, the behavior of the wire ropes and their life expectancy appear relatively clear, and changes in materials are dictated strictly on an economic basis.

C. Conclusions and Recommendations

1. Conclusions

a. Rope material is specified poorly at present.

b. The major materials failure problem is fatigue coupled with abrasion and, on occasion, corrosion.

c. Independent wire rope core has a very short lifetime under fatigue conditions.

2. Recommendations

a. Processes that improve the materials currently specified for wire should be incorporated in updated specifications.

b. Other possible steel compositions and microstructures should be investigated.

c. Studies should be initiated to consider fatigue, wear, and corrosion characteristics of materials most likely to be used for wire, to improve the materials for independent wire rope cores, and to improve all stages of wire-making processes to optimize wire properties. For proper evaluation of candidate materials, specific rope designs made from such materials should be tested under simulated operating conditions to determine their susceptibility to fatigue (including corrosion), abrasion, overloading, and brittle cracking.

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VI. ENVIRONMENT AND WEAR

Wire ropes obviously should be changed before failure occurs but, equally obvious, ropes in good condition should not be discarded since they are expensive. Also, in many instances, changing a rope under service conditions is difficult, dangerous, and time-consuming. Thus, it is important to define and analyze the factors that cause wear and strength degradation in order to determine when wire rope should be removed from service.

This section discusses the mechanisms of the chemical and physical deterioration of metallic wire ropes. Chemical or environmental degradation is treated in some detail since it often is very difficult to detect and is not fully understood or appreciated by most users. Also, chemical or environmental conditions strongly affect physical properties such as fatigue resistance. Physical deterioration is equally important in determining the useful life of mechanical rope but it is discussed more briefly because its causes and effects are more obvious to reasonably well-trained maintenance personnel. Lubrication of wire rope also is discussed briefly.

A. Chemical Deterioration

The environmental influence on wire rope life is considered in two principal categories: the environment created within the rope by the external environment and the external environment itself.

In many, if not most, cases the internal environment will be a more potent factor in limiting rope life than the external environment. The internal environment results from the accumulation of liquids, salts, and corrosion products within the interstices. These entrapped liquids generally become more acid than the external environment as a result of the acid nature of corrosion products of metals used for ropes. Such corrosion products, resulting from the action of salt water, can reach a pH less than 3 as compared with a pH over 8 for natural seawater.

The crevices formed between overlapping wires and overlapping strands become prime corrosion sites through the action of "concentration cells" resulting from the differences in concentration of dissolved oxygen and ions in the liquids within the crevices and the liquids in contact with the external rope surfaces. The most harmful concentration cells are based on differences in concentration of dissolved oxygen. In these cells, the metal surfaces in contact with the depleted oxygen liquid within the crevices will be anodic to the metal surfaces in contact with the aerated liquids outside the crevices and will suffer corrosion accelerated by the differential aeration or concentration cell current. A potential difference of over 100 millivolts can be developed on steel surfaces by such cells in seawater.

Alloys, such as stainless steels, depend on passive oxide surface films for corrosion resistance. These oxide coatings break down in crevices where the liquid is depleted of the oxygen required to preserve passivity and the simple differential cells become augmented greatly by what are called "active:passive" cells. In such cells on stainless steel surfaces, a potential difference well over 0.5 volt can develop between activated surfaces that have lost their passive films within crevices and the surfaces that retain their passivity outside the crevices. Such powerful active:passive cells are aggravated even further by the strongly acidic nature of the corrosion products that become trapped within the crevices. These cells are particularly damaging because, in addition to accelerating the corrosive attack within the crevices, the metal surfaces in contact with acidic chloride solutions cannot be repassivated. In extreme cases with ropes made from the commonly used stainless steel types 302, 304, or 316, individual wires have suffered internal corrosion that progressed along the length of the wires, converting the wires into thin-walled tubes having little or no strength.

Similar crevice corrosion of stainless steel has been observed within the crevices formed between ropes and their swaged terminal fittings. Here, the attack is more severe than within the rope crevices because the rate of crevice corrosion increases as the area of freely exposed surface outside a crevice increases relative to the area within the crevice. Therefore, any material, such as stainless steel, that is used for rope must be able to tolerate the corrosiveness of the environmental liquid in inevitable crevices without suffering accelerated attack.

Zinc- or aluminum-coated steel depend on sacrificial corrosion and are much less susceptible than stainless steels to crevice corrosion in seawater. The principal effect of crevices on the corrosion of zinc- or aluminum-coated or uncoated steel rope is to entrap corrosive liquids and salts and to delay drying when taken from the water or used only in air.

Bare or plain carbon steel rope is particularly vulnerable to attack in the splash zone just above the high tide level where rates of attack can be over five times greater than in the zones below the tide level, and more than twice as great as in the atmosphere above the splash zone. Corrosion of zinc and aluminum coatings on steel are affected greatly by the velocity of flow of seawater over the rope surfaces (This has been demonstrated by tests on zinc- and aluminum-coated steel wires in seawater at Harbor Island, North Carolina.)

The crevice corrosion cells that are principally responsible for the short life of stainless steel ropes submerged in seawater are not developed in air environments involving only salt spray or salty atmospheres. Consequently, while stainless steel ropes are inferior to zinc- or aluminum-coated steel ropes when submerged in seawater, they are more durable than coated steel ropes under atmopsheric exposure only.

Stainless steel ropes suffer accelerated attack, analogous to crevice corrosion, on surfaces that are embedded in bottom muds. However, embedded surfaces are not a serious problem with bare or coated steel ropes. In ropes extending through water in different depth zones with variations in dissolved oxygen content, corrosion can be accelerated by the action of different aeration or oxygen concentration cells.

Corrosion may be reduced or eliminated by the application of protective electrical currents to achieve cathodic protection. The protective current may come from a galvanic anode, such as high purity zinc or properly alloyed aluminum, or from a battery or rectifier through an appropriate electrode. In any case, the electrodes supplying the protective current must be positioned to provide sufficient current to reach all surfaces requiring protection. Zinc or aluminum galvanic anodes are dissolved by this practice and, hence, must be inspected and replaced.

Metals sensitive to hydrogen may be embrittled by the hydrogen that can be generated at the metal surface by a cathodic protection current. The cathodic protection potential of high-strength steel probably should not be allowed to exceed about -1.0 volt, as measured with a saturated calomel half cell.

Coatings (e.g., nickel or copper) that are more noble than the underlying steel not only fail to provide cathodic protection to bare spots on the steel but greatly accelerate attack at such bare spots. Attempts to protect type 304 stainless steel rope wires by coating them with a 90 percent copper-10 percent nickel alloy were unsuccessful because this alloy, while being anodic to, and capable of, cathodic protection of the 304 alloy in its passive state, was cathodic to this alloy in its active condition.

High-strength alloys have been developed that are substantially free of corrosion in seawater under all the described environmental conditions. This corrosion resistance, along with high levels of endurance to corrosion fatigue, includes resistance to crevice corrosion, bottom muds, and stress corrosion cracking. However, some of these alloys are difficult to fabricate into wire ropes. The unsatisfactory surface properties of others (e.g., titanium) lead to failures by "fretting" (or galling) under the stresses and movements encountered in use. Some materials proposed for ropes may suffer severe "temper" embrittlement at temperatures resulting from friction in sliding contacts or in terminal connections made with molten zinc. Such temperature effects must be investigated to qualify materials for use in wire ropes. Temper embrittlement is especially important with highly alloyed materials at very high strength levels (e.g., over 250,000 psi yield strength). Also, highly corrosion-resisting ropes have failed as a result of improper design of terminals and attachments or other mechanical features of installations.

Apparently, problems arising from corrosion of rope materials may solved by more attention to mechanical details and environmental exposure than to further improvements in the corrosion resistance of candidate alloys for corrosion-resisting ropes. One obvious requirement is that alloys used for ropes must be resistant to stress corrosion cracking. This property can be evaluated by currently available test methods on either the wire materials or on the rope itself, under any of the natural environmental conditions likely to be encountered, if the microenvironments within the rope under service conditions are known and duplicated. Materials proposed for the manufacture of wire rope should be established as being free from susceptibility to stress corrosion cracking in the user's environment before being considered for the manufacture of wire rope.

One of the more critical properties of a wire rope material is the ability to withstand corrosion fatigue in applications involving cyclic stresses in a corrosive environment, such as ropes frequently passing over sheaves in salt water. The effect of a corrosive environment in lowering the ability of a material to resist cyclic stresses can be demonstrated readily by fatigue tests on rope materials. Such tests can be made using specimens in the form of machined bars acting as cantilever loaded rotating beams. Also, specimens can be tested in the form of wires as supplied for the fabrication of ropes. Because of the many and complex environmental factors involved and the environment simulations, such tests only rank the materials in a reasonable order of merit for resisting corrosion fatigue.

Data indicate that wires strengthened by cold drawing are much superior in resistance to hydrogen embrittlement and corrosion fatigue than wires strengthened by quenching and tempering heat treatments. The most striking conclusion from tests of many steels ranging from 35,000 psi to 250,000 psi in yield strength is that corrosion fatigue resistance cannot be attained by increasing the yield strength of the steel unless a substantial improvement is effected in its resistance to corrosion. For example, at 100,000,000 cycles in seawater, two steels -- one with a yield strength of 250,000 psi and the other with yield strength of 35,000 psi -- had the same stress corrosion endurance limit of 3,000 psi.

B. Mechanical Deterioration

Wire rope in service deteriorates mechanically even in the absence of a corrosive environment. There are many well known mechanisms of mechanical deterioration or damage, including abrasion, crushing, kinking, static or dynamic overloads, causing broken wires or strands, and mechanical fatigue of individual wires caused by bending the rope over sheaves or drums. The causes and cures of these problems are well known, and these problems are recognized even by relatively untrained personnel. The existing training manuals or handbooks on rope do not adequately treat these mechanical damage problems (for example, NAVSHIPS Technical Manual, Chapter 9270).

The major difficulties in controlling failures due to mechanical damage to ropes involve choosing the optimum rope construction for a particular application and establishing quantitative limits of mechanical damage (e.g., the permitted number of broken wires per lay length and the reduction in diameter) before the rope is removed from various types of service. The choice of an optimum rope for any particular service application is made difficult by the bewildering variety of rope constructions available. Experienced rope engineers treat this problem as an art and agree upon only a few basic tenets. However, as a miminum, it should be possible to rank numerically various rope constructions in terms of their resistance to damage by crushing, abrasion, or bending over a small radius.

Criteria for retirement of a wire rope based on quantitative measures of mechanical damage are difficult to establish but they are within the state of the art. Certain industries already have established retirement criteria for wire ropes in specific uses. For example, the retirement of mine hoist ropes in the United States presently is based on visual inspection, age, and tons or ton-miles of hoisting duty; the more stringent state codes require the changing of a mine hoist rope if it is kinked, has six visible broken wires per lay length, has 35 percent or more wear in the crown wires, or exhibits marked corrosion. At present, a set of federal inspection standards for mine hoist ropes is being prepared. Elevator ropes, construction crane ropes, and ski lift ropes are inspected similarly. The mining and elevator industries have established excellent safety records for hoisting men and materials with wire rope. Their criteria for rope retirement due to mechanical deterioration, along with NDE methods (discussed in Appendix D) to determine internal damage due to corrosion and/or fatigue, would be an excellent base upon which to build retirement criteria for ropes used in critical DoD installations. Less critical service requires less stringent retirement criteria and this is true in current industrial usage as well as DoD applications.

C. Lubrication

Lubrication of mechanical ropes needs further study. Initially, fiber core ropes are lubricated internally by the manufacturer. One purpose of the fiber core is to serve as a reservoir of lubricant for the rope. IWRC ropes have, of course, less effective internal lubrication. Common industrial practice (required by state and federal codes in some applications) is periodic painting, spraying, dripping, or splashing various oils or greases onto the ropes externally. The value of this practice has been questioned and, conceivably, a poorly chosen lubricant could accelerate internal corrosion.

Oils and greases, applied as lubricants in the manufacture of wire ropes and for corrosion protection in service, afford some degree of protection in storage and in use in mildly corrosive environments, such as exposure to the atmosphere on drums or winches when the ropes are not in use. Such coatings applied to the external surfaces of ropes may not penetrate into the interstices into which corrosive liquids have penetrated if the protective greases are too viscous or if the application is made at too low a temperature. Radioactive tracers have been incorporated in greases to show the extent of penetration of greases under service conditions, and additional investigations using this technique could be warranted in evaluating protective greases and their application methods.

D. Conclusions and Recommendations

1. Conclusions

a. The corrosion and corrosion fatigue of wire rope are important factors in the life of rope.

b. Internal corrosion is not detected easily and is a main contributor to rope failure.

c. The causes of mechanical deterioration or damage (such as abrasion, crushing, kinking, broken wires or strands caused by static or dynamic overloads, and mechanical fatigue of individual wires caused by bending the rope over sheaves or drums with too small a diameter) generally are preventable.

d. Criteria for retiring wire rope based on quantitative measures of mechanical damage are difficult but not impossible to establish.

e. The principles and designs (such as those of fiber core) for lubricating wire ropes are not understood fully.

2. Recommendations

a. Research and development should be continued on corrosion protection of wire rope, particularly as related to reducing internal corrosion.

b. A data review and/or research should be initiated to rank the various rope constructions in terms of their resistance to damage by crushing, abrasion, or bending over a small radius.

c. Existing information in wire rope handbooks on precautions to prevent mechanical damage, although often inadequate, should be reiterated often to operating personnel.

d. Nondestructive evaluation programs should be initiated or continued to develop criteria for retiring rope due to corrosion and/or mechanical damage.

e. A continuing effort is needed to determine rope design principles (including the use of fiber cores) for maintaining the lubrication necessary to prolong rope life.

VII. TESTING, INSPECTION, AND MAINTENANCE

This section is devoted to test and inspection methods available for determining the mechanical and other properties of basic rope elements.

Testing and inspection of rope and its elements are still largely empirical procedures, and the selection of test conditions is dictated by a combination of available funds and reliability needs. Various approaches simulating specific service conditions have been used but, lacking basic knowledge of rope element interactions and exact stress conditions in each rope element under service, extrapolation from test data must be treated very cautiously.

The following testing is considered in detail:

1. Tests of rope elements.
2. Proof and tensile tests of rope to determine a required minimum standard.
3. Simulation tests to determine rope properties under service conditions.
4. Nondestructive testing techniques to determine variations of rope properties based on established standards.

Nonmechanical testing, such as metallographic studies on wire, usually are performed routinely. Tests for nonmechanical properties other than those required for simulation or nondestructive testing are not considered here. Environmental testing is considered only in terms of its effect on mechanical property testing.

A Survey of Rope Testing, Appendix F, provides an indication of testing and analysis being performed internationally.

A. Testing of Rope Elements

Mechanical testing of wire is one of the principal routine quality controls in rope fabrication. Estimates of wire ductility also are made by recording the twists to failure of a straight wire loaded in torsion during routine quality control torsion tests. The objective of these tests is to evaluate the cleanliness of the steel, quality of the wire drawing, the wire surface, and heat treatment of the rope wire. Generally these tests are performed on a straight wire held between suitable grips.

In addition to simple tensile and torsion testing, data have been gathered on fatigue properties of wire for rope. Test data have been produced on various machines (such as axial loading, torsional loading, and special loadings) that are more representative of the actual combination of twist, bending, and tensile loading of wire in a stressed rope. Most reviewed data did not give the ambient conditions of testing but a few reports describe the effects of specific environments on fatigue. Test equipment (such as that at the disestablished Battelle facility at Long Beach, California) has simulated complex stressing of the wire during fatigue testing (including fretting effects) but Battelle's testing was not conducted under various environmental conditions. Another unevaluated factor is the effect of local heating that occurs during mechanical testing and results from the stresses imposed by the mechanical work (e.g. cyclic fatigue testing).

No test data on the mechanical properties of nonmetallic rope constituents, such as core material and lubricant, appear to have been documented. The effectiveness of these materials generally is established by incorporating them in an experimental rope and then studying the rope properties.

B. Tensile and Proof Testing of Rope

Tensile tests on rope are performed as proof and sample testing. A proof test is done on a complete service length of a given rope by stressing the rope to a specified load above its assumed safe service load, measuring the resulting strain, and noting the presence of any fractures. Sometimes a load is applied primarily to pre-stretch the rope. Generally, the tensile strength of a wire rope is determined by destructively testing an end section of that rope. Tensile testing is used primarily in inspecting lots of rope to determine their conformance to applicable specifications. For example, some comprehensive programs exist for testing all rope for mine hoists before entering service and at regular intervals during service. Figure 4 presents the information required by the Ontario Division of Mines, Canada.

In the above test methods, loads are applied axially only, and environmental conditions are unspecified. In most cases, failure appears to commence with the parting of an exterior wire followed successively by fracture of more exterior wires and, finally, fracture of one or more strands. As individual wires fail, the rope extends and its diameter decreases. Failure is interpreted not as a complete separation of the tensile specimen into two or more parts, but rather as a significant reduction in the load-carrying area of the specimen. No quantitative expressions are attached to the term "significant."

The first parting of one surface wire indicates that the load distribution across the rope is not necessarily uniform. In addition to the nonuniform stress distribution inherent in a rope construction, loading differences may be imparted by fittings and sheaves.

It appears desirable to determine rope behavior under other than purely linear tensile loads. For instance, at present, the concept of flexibility is not described quantitatively by any tests. Those familiar with rope realize that a rope made of many fine wires has better flexibility than a rope of the same tensile capacity but made of a few large-diameter wires. In any case, describing a rope by its breaking strength, construction, and flexibility number might be a better indication of rope behavior under service conditions than the present method of describing a rope by its construction and breaking strength.

TEST NUMBER.. DATE..

TEST FOR.. MINE..

ROPE No.................. REEL No.................. SHAFT No.................. COMPT. No..................

WT. CONVEYANCE..............LBS. TOTAL LOAD..................LBS. ORIG. STRENGTH..................LBS.

NOMINAL DIAMETER..........." No. STRANDS.................. No. WIRES PER STRAND..................

CONSTRUCTION OF STRAND..

DIAMETER OF WIRES..

EXTERNAL APPEARANCE OF ROPE..

INTERNAL APPEARANCE

LUBRICATION—Exterior of strands. Visual Rating.................. Character..................

Interior of strands. Visual Rating.................. Character..................

Rope Core. Visual Rating.................. Character..................

CORROSION AND EROSION—Outer wires. Visual Rating..................

Inner wires. Visual Rating..................

Filler wires. Visual Rating..................

DIAMETER OF ROPE AT 0#..................Wt. Convey..................Total Load..................½ Orig. Str..................

LENGTH OF TEST PIECE.................. BREAKING LOAD..................LBS. EXTENSION..................

STRANDS BROKEN.................. LOCATION OF BREAK..................

TORSION TESTS

Average number of twists in 8" lengths { Outer wires.................. / Inner wires..................

ORIGINAL TORSION TESTS

Average number of twists in 8" lengths { Outer wires.................. / Inner wires..................

REMAINING STRENGTH..................% ORIGINAL STRENGTH..................LBS. = 100%

PRESENT EXTENSION..........." ON..........." ORIGINAL EXTENSION..........." ON..........."

NOTE: ORIGINAL DATA BASED ON TEST No.................. DATE..................

VISUAL RATING:

LUBRICATION—CHECK CONDITION OF YOUR ROPE WITH RATINGS GIVEN IN TEST REPORT

CHARACTER—Viscous (normal); gummy; caked

STRANDS

1. Good Normal amount as in new rope.
2. Fair Lubricant somewhat depleted.
3. Poor Very little lubricant present.
4. Dry No lubricant left or completely decomposed.

ROPE CORE

A. Good Greasy and flexible. Well lubricated.
B. Fair Lubrication fair. Core not deteriorated.
C. Poor Little lubrication. Core hard.
D. Dry No lubrication. Core hard and dry.

CORROSION

o. No. Corrosion.
i. Very slight corrosion. Merely a reddish brown film on the wire.
ii. Corrosion scale well established. Some pitting of surface.
iii. Surface of wire completely scale covered. Some well established pitting.
iv. Surface completely corroded. Numerous deep pits.
v. Surface completely corroded. Considerable loss of section. Only narrow ridge between pits.
vi. Very severe corrosion. Loss of section up to 1/3 metal. Pits joined forming grooves.

REMARKS..

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SGD..

CABLE TESTING LABORATORY, WHITNEY BLOCK, PARLIAMENT BLDGS., TORONTO M7A 1X4

FIGURE 4. Sample Tensile Test Report (from Cable Testing Laboratory, Toronto).

C. Simulation Testing of Rope

Simulation tests comprise a partial replication of a rope system including means of applying varying loads, changing the direction of the rope, and varying environmental conditions; they are designed to approximate the conditions of fatigue, wear, and abrasion in service. A simulation system may vary from a simple reciprocating loading device connected to a rope around a sheave, to a dead-loaded end,* to a complex system of arrays of sheaves forcing the rope through various bend reversals.

Such simulation systems are used occasionally as tests for the components, other than the rope, in the system. For instance, the former Hunter's Point Naval Shipyard (San Francisco, California) had a rope and sheave system capable of simulating the relative motion between two ships at sea. It was used principally to test winches and tensioning arrangements rather than the rope. Unfortunately, through all the years of the Navy's testing of their FAST System, no data were accumulated concerning rope and related components.

D. Nondestructive Testing Methods

Nondestructive testing is used in inspecting rope to determine the presence of any flaw that might affect deleteriously the performance of newly purchased rope and of ropes in service. The objective in maintenance inspection is to determine when a rope becomes unsafe for future use and must be retired.

Nondestructive testing and evaluation standards should be based on the results of destructive testing of specimens that indicated flaws by NDE prior to destructive testing, that were taken from ropes from the procuring stage through the various maintenance stages, and that were obtained from ropes providing satisfactory and unsatisfactory service. To date, insufficient data have been accumulated upon which reliable inspection to NDE standards may be based. The

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* The dead-loaded end would be free either to rotate (as with a swivel or free-hanging weight) or constrained to prevent rotation, depending on the parameters of the simulation test itself.

types of flaws that can be determined at present by NDE (primarily visual inspection) are broken wires (particularly near the surface of the rope) and loss of cross-sectional area due to advanced corrosion.

Of the available nondestructive test methods, electromagnetic testing has been used most extensively because of the flexibility of equipment and because the ferromagnetic nature of the rope produces suitable signal-to-noise ratios on the hunted flaws. Electromagnetic methods can be applied in two ways. First, an electrical conductor can be surrounded by changing electric or magnetic fields, and currents will be generated within the conductor. In turn, these currents will react with the exciting field and the excitation or relative reaction will be a function of the conductivity and the nature of the conductor. The reaction can be picked up either directly by changes in the exciting field or by a circular probe, called a search probe, containing either a small coil or a Hall element that is connected to suitable instrumentation to show the changes in the induced voltage or the phase relationship of the induced voltage to the field. The second type of electromagnetic instrument depends on the generation of a constant field by direct current carrying exciting coils.

All electromagnetic systems are sensitive to any change in the electromagnetic characteristics of the material, such as metallurgical changes caused by work hardening. A number of methods have been proposed to reduce this effect; they generally are based on a type of bridge circuit comparing the test rope as a standard rope or feeding a signal presenting a standard rope into a bridge circuit.

Another problem in electromagnetic testing is the possibility of a variable cross-flux between the various wires within the strands of the rope. Hence, most electromagnetic testing methods have compared the state of the rope before and during service to that of a standard rope. In the latter instance, tests can be performed under similar loading conditions on the rope eliminating one of the possible variables in testing. These test instruments have found the widest application in mine shaft hoist ropes because of the vital importance of these ropes to mine safety and economy. Permanent records of this test can bo maintained readily.

Probably the most developed inspection system exists in Canada, where regular inspection by an approved electromagnetic testing system is made compulsory (Ontario Department of Mines, 1971). A side benefit of this nondestructive inspection is that, simultaneously, a stringent visual inspection of the hoist ropes also is performed. With the introduction of regular inspections, the mine operators and the province of Ontario noted a considerable improvement in the economy and service life of hoisting ropes. The improvement may have been due to the application of nondestructive testing methods or to the regular inspection by a more or less permanent staff.

In addition to the two electromagnetic systems cited above, a number of improvements on these approaches and other instrumentation have been suggested (Larson et al., 1971). However, as of 1973, most of these other approaches seem to be in the pilot or laboratory stage.

One of the unsolved NDE problems is the assured detection of subsurface wire fractures. Relatively little use has been made of radiography that might be sensitive to subsurface wire fractures. Recent radiographic developments do permit rapid inspection and could be applied to the testing of rope as it passes through a test station. The disinterest in radiographic techniques probably is due to the shorter time consumed by the well-established methods and the fact that radiographic inspection of long rope could be an elaborate procedure. Nonetheless, modern radiography is particularly promising since methods have been developed that use computer interpretation of the X-ray to eliminate the mass of unwanted signals occurring in sound rope; only signals relative to reactions with flaws are shown. These methods have been applied successfully to advanced composite materials. Materials like rope consist of a multitude of filaments interwoven in a complex pattern. Transferring some of the technology now used in inspecting composite materials to the rope field could be a very fruitful area of technology transfer.

An NDT method could be related directly to properties, such as modulii, by measuring the internal friction (or damping relationships) and resonant frequency of vibrations of a rope test section. Investigations have been carried out in the laboratory (Kawashima and Kimura, 1952; and Kimura, 1971). One method based on measuring resonant frequency has been used to determine the stress in a rope in service. In this method, an accelerometer is attached to the suspended rope. In service, the rope's speed of vibration is translated by the accelerometer into signals that indicate changes in resonant frequency and are attributed to a change in stress.

Another nondestructive method that has been applied to the direct measurements of the stress in a rope is the measurement of the speed of transmission of an ultrasonic pulse (Vanderveldt and Gilheany, 1970).

The acoustic emission test recently has aroused interest and is being tried in many applications even though it has many limitations (including temperature effects, probe coupling and arrangement, and the need to filter out background noises). Acoustic emission is based on the fact that a metal which is loaded to a stress level close to its yield point emits minute acoustic pulses caused by the movement of dislocations as plastic deformation begins. The integrated sum of these pulses over a stress cycle may be related to the microcracks within the material and their coalescence into gross cracks. The power output in acoustic emission testing of a strained part, such as the rope, is extremely minute and amplifications on the order of 10^6 are required to make those signals apparent. Furthermore, these signals are only apparent while the rope is being strained either by a direct load or when passed around a test pulley. Thus, this method may be suitable for checking a rope in service. For acoustic emission, as in measuring ultrasonic pulses in rope, transducers can be applied to the end of a wire to translate the acoustic signals to an electrical signal. Thus, they can be buried within a winding drum. The wire in the rope acts as a wave guide, particularly in the case of high-frequency signals, and attenuation therefore is minimized.

The use of standard ultrasonic methods to inspect rope is complicated by the need either to interrogate each wire separately from the end of the rope or to send an ultrasonic wave beam across a very complex body of various materials. Similar to cross conduction between wire strands, ultrasonic interaction and coupling occurs to a widely varying degree in rope because of factors such as the grease content and the counter force between wire strands. Therefore, routine ultrasonic methods are not very promising for rope inspection.

A simple approach to the measurement of rope wear is measuring a lay length. Normal extension with use is a result of extrusion of internal lubricants and general settling of the core. Fracture of a number of wires in a lay results in a disproportionately large extension of the wire rope within that particular lay length. This simple approach is feasible in examining short lengths of rope but impractical for inspecting long rope lengths such as those used for mine shafts or large hoisting equipment. However, a number of possibilities exist that might permit alternate divisional inspection of lay lengths. For instance, the reflection of a small light beam by a surface wire could be used to record the completion of the lay. To date, such methods have not been explored extensively.

E. Maintenance of Rope and Rope Systems

No single, definitive manual or handbook was found that adequately covers the subject of maintenance. The rope manufacturers' catalogs and handbooks are the best source of information, but they are not consistent or complete. Mark's Handbook is silent on the subject. Additionally, some good information concerning maintenance is to be found in the following:

1. The American National Standards Institute's ANSI B30.x series dealing with cranes and hoisting equipment.

2. ANSI Standard M11.1 dealing with wire rope for mines.

3. The American Petroleum Institute's API Recommended Practice RP-9B, Application, Care, and Use of Wire Rope for Oil Field Service.

4. Offshore Operators Committee, Manual of Safe Practices in Offshore Operations.

Other documents have sections or chapters dealing with rope maintenance but these, too, are not comprehensive and usually duplicate each other.

Even the U. S. Navy (the major government user of wire rope) does not have an up-to-date manual on the subject of maintenance. The generally referenced Navy document for new construction and routine daily maintenance, Technical Bulletin No. 5, "Instructions for the Design and Care of Wire Rope Installations," was issued last in January 1946. Many references in this bulletin go back to the 1930's. Other Navy publications, such as Knights Seamanship and training course books for Boatswains Mates, are not as out of date but certainly are not comprehensive.

While certain areas relating to rope maintenance need further development or research, sufficient technology and experience currently exist to allow the immediate preparation of a comprehensive handbook for the maintenance of rope and rope systems. Undoubtedly, such a handbook should be based on the proposed standards and handbooks as well as on information readily available from manufacturers. This handbook should include maintenance data on rope fittings such as sockets, shackles, sheaves, and more complex fittings such as equalizers, Carpenter's Stoppers, and similar grips.

F. Conclusions and Recommendations

1. Conclusions

a. Destructive tests used for rope qualification and development purposes have not been correlated to service conditions.

b. The present practice of using breaking strength and rope construction to indicate rope behavior in service is inadequate. Adding other criteria, such as the flexibility number, might help the correlation between testing and service.

c. Nondestructive test methods are in the developmental or limited use stage abroad. However, their application, particularly to the detection of corrosion or inner wire breaks, has not been established adequately.

d. The nondestructive evaluation technology that is used to inspect composite materials might be applicable to rope inspection.

e. Adequate technology exists to support the preparation of a comprehensive handbook on the maintenance of wire rope and wire rope systems. Such a handbook is not available and is needed badly.

f. U. S. Navy Technical Bulletin No. 5 is outdated technically.

2. Recommendations

a. Rope tests should be developed that correlate with actual service conditions. Theoretical studies and routine and service simulation test data on all rope development programs should be coordinated with rope types and conditions so that the data may be a useful foundation for continued work.

b. Nondestructive test methods should be developed based upon the correlation with destructive tests of specimens, initially subjected to NDE. The specimens should be selected from newly procured and in-service ropes that are considered as satisfactory and unsatisfactory.

c. The preparation of a comprehensive handbook on maintenance of rope and rope systems is recommended strongly.

d. A current authoritative bulletin should be prepared and issued to replace the existing Technical Bulletin No. 5.

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VIII. REVIEW OF FEDERAL SPECIFICATION RR-W-410C, NAVY TECHNICAL BULLETIN NO. 5, THE SUPPLY SITUATION, AND INTERNATIONAL STANDARDIZATION

Within the Department of Defense, rope specifications have been maintained by the U. S. Navy. These specifications now cover approximately 3,000 kinds and sizes of rope. As developments occurred, additional kinds, sizes, and special requirements were included in specifications and, hence, a difficult major supply system exists.

To a limited extent, rope is covered in specifications for more general equipment (e.g., towers, cranes). On the international level, standards are being developed for rope and related equipment by such groups as the International Standards Organization (ISO) Technical Committee 105. Within the United States, the American National Standards Institute (ANSI) has a good specification on rope for mines (M 11.1 — 1960).

A. Federal Specification RR-W-410C

The basic document used by the military for procuring general purpose wire rope is Federal Specification RR-W-410C, "Wire Rope and Strand," dated September 1968, over which the U. S. Navy has cognizance. The following comments are applicable to this specification:

1. Scope of Choice

The specification should be revised to simplify understanding. The many provisions for different rope types and constructions have been considered confusing to the design engineer and ordering logistician.

2. Strength Test Tolerance

In the tables of the specification, there is a consistent footnote as follows: "The acceptance strength shall not be less than two and one half percent below the nominal breaking strength." In effect, this footnote establishes the minimum breaking strength at 2½ percent lower than the values listed in the tables and could create a problem for an unwary design engineer. The Committee believes that the breaking strength in the Tables either should be reduced by 2½ percent, or the breaking strength should be stated as a minimum. As an example, in API Specification 9A, each table shows two breaking strengths — nominal breaking strength and minimum breaking strength — clearly indicating minimum breaking strength as the design criterion.

3. Lubrication

The specification is silent regarding lubrication. During the manufacturing process, lubrication is applied internally and to the external surface of a wire rope and is often an essential procurement feature. A comprehensive treatment should be included in the federal specification, since apparently lubrication is an important factor in rope life and wire rope often is not lubricated in use.

4. Length of Lay/Pitch

Length of lay or pitch of rope is an important rope characteristic when "Carpenter's Stopper" rope grips are used by the Navy. API Specification 9A, Article 4.1, refers to length of lay but specifies the tolerance only in the plus direction. The effect of lay lengths on the properties of wire rope should be investigated to determine whether specification of this characteristic is necessary.

5. Ordering Format

The inclusion of a sample format for generating a complete specification of a given rope is advisable because the information in RR-W-410C is extensive and requires many decisions concerning wire rope parameters by the ordering engineer. Other federal/military specifications include such formats. The sample might include items such as the diameter, construction, regular lay versus lang lay, righthand versus lefthand lay, core material, galvanized versus nongalvanized, type of galvanizing process, lubrication, special end fittings, and others. This feature should improve the engineering of wire rope rigging systems and the ordering of rope therefor.

B. Technical Bulletin No. 5

This bulletin, issued in 1946, is the only Navy primer on the design and care of rope installations. Since it is very outdated, it should be replaced by a current manual on the design and maintenance of rope.

C. U. S. Naval Supply System

The U. S. Naval Supply System would require an extremely large number of rope types and sizes to stock all the ropes covered by Specification RR-W-410C. The supply system has been unable to maintain such stocks, and indiscriminate substitution probably occurs on a size-for-size basis without regard to other design parameters. One recommended solution is to reduce drastically the general purpose ropes carried as stock items, with other ropes being special order. In ropes of special order, specified substitutes could be listed as alternates as a means of controlling indiscriminate substitution.

D. International Standardization

The U. S. Navy could benefit greatly from participation in the International Standards Organization Technical Committee 105 (ISO/TC105), since its standards could provide assurance of quality rope in emergency overseas procurement and could reduce excessive shipboard storage of rope. Costs might be reduced by this increased flexibility in procurement to acceptable international standards.

E. Conclusions and Recommendations

1. Conclusions

a. Specification RR-W-410C is too encompassing to meet today's needs adequately and requires the U. S. Naval Supply system to stock costly diverse items that are virtually impossible to maintain physically.

b. Technical Bulletin No. 5 is very outdated and should be replaced by a current manual on the design and maintenance of rope.

c. Membership in the ISO/TC105 as a participating member might assure obtaining quality rope in emergency overseas procurement. Such action could reduce costs and excessive shipboard storage of rope.

2. Recommendations

a. Immediate revision of Specification RR-W-410C is recommended to make it more responsive to DoD's needs and to reduce drastically the number of specified general purpose ropes.

b. The preparation of a completely new handbook is recommended to replace Technical Bulletin No. 5. This manual should incorporate the latest design and maintenance information available from the major producers and users of wire ropes.

c. Membership in the ISO/TC105 as a participating member is recommended as a mechanism for obtaining quality rope in overseas procurement.

APPENDIX A

THE NAVY AND WIRE ROPE *

Over the past decade the uses of wire rope in the U.S. Navy have become so diverse, sophisticated, and costly that the guidelines and criteria developed and established for yesterday's systems and system operations and maintenance are marginally adequate and cannot be used with confidence in today's applications. Operations such as deep sea mooring, at-sea replenishment of delicate missiles, shipboard handling of submersible vehicles, and accurate deposition of systems in sea floor construction have accentuated the need for a better understanding of wire rope as a system and especially its reactions in a marine environment.

The fact that the Navy wire rope purchases are well over $10 million (1969 dollars) annually, with a large percentage of this amount representing replacement, is worthy of mention. Battelle Memorial Laboratory in its logistic-oriented final report, Investigation of Wire Rope Service Requirements and Design Parameters for the U.S. Navy, cited the fact that the high cost of labor in wire rope replacement in certain cases far overshadows the actual cost of the wire rope itself. In the same report it was pointed out that inventory management, quality control, cataloging, and procurement are major wire rope problems in the U.S. Navy. These factors, although logistically oriented, bear heavily on the engineering and operational aspects of wire rope. Another feature that is considered (perhaps not as often as it should be) in engineering systems that have wire rope as a component, is the maintenance level that the wire rope will receive.

On investigating wire rope problems, the Naval Ship Systems Command and the Naval Ship Engineering Center have initiated a new approach that will consider the total aspects of wire rope systems from the scientific analysis of the wire rope materials through construction, usage, environment, and maintenance in Naval use.

*Prepared for the Committee by John F. Wynn, Jr., Naval Ship Engineering Center, Hyattsville, Maryland; March, 1972.

A. Analysis of Literature

An analysis was made of areas of information in existing wire rope literature to provide an input for the definition of a comprehensive wire rope research and development program. These areas were identified in terms of 21 defined wire rope factors and four levels of research, development, testing, and engineering (RDT&E) work (theoretical analysis, engineering, design, test and evaluation, and general technical information usage and failure reports). The wire rope factors are: (1) bending fatigue, (2) complex arrays, (3) construction, (4) corrosion, (5) crushing, (6) equipment, (7) human factors, (8) maintenance, (9) material, (10) specifications, (11) static response, (12) stowage, (13) structural elements, (14) supply, (15) tensile fatigue, (16) terminations, (17) test equipment, (18) transient response, (19) twist, (20) vibration, and (21) wear.

The analysis was conducted in two parts: (1) a comprehensive analysis of approximately 800 articles that had been listed previously in a bibliography on wire rope prepared at the Naval Ship Engineering Center under Task A of the program; and (2) a more detailed analysis of approximately 225 of the 800 articles for which the complete texts were available. The analysis indicated that the factors covered most intensively in the 800 articles were, in descending order of importance:

- Bending fatigue
- Materials
- Analysis of complex wire rope arrays
- Corrosion
- Equipment
- Wire rope structural elements.

The levels of RDT&E of the information were: general discussion, 34 percent; test and evaluation, 30 percent; theoretical analysis, 25 percent; and engineering, 11 percent.

B. Wire Rope Problems in Applications

As another part of the study, problems and priorities relative to wire rope were determined from interviews with a cross section of cognizant activities. Problems were defined and ranked in terms of the 21 specific wire rope factors previously mentioned. Construction and corrosion of wire rope and problems that are caused by personnel were ranked as the most important problem areas. The most important wire rope problem area for six general types of wire rope applications are shown below.

Applications	Most Important Problem Area
Helicopter minesweeping	Construction
Moors	Material
Oceanographic	Equipment
Salvage	Stowage
Surface and under-ocean systems	Construction
Underway replenishment	Equipment

C. Government Specifications and Manuals Analysis

Government documents pertaining to wire rope were reviewed to determine their adequacy in meeting the requirements of the wire rope design engineer, installer, user, maintainer, and supplier. The documents, including specifications, supply catalogs, technical bulletins, manuals, and handbooks were analyzed in the light of wire rope problems and requirements reported by the Fleet and by the Navy management under prior phases of a comprehensive Navy wire rope research and development program. The principal findings are:

1. Coordination of development and dissemination of wire rope information is necessary.

2. Current documents are not adequate for the wire rope design engineer.

3. Current documents do not adequately meet the requirements for personnel training for optimum wire rope utilization.

4. Standardization of wire rope systems is inadequate.

Wire rope related documents, used by the Navy Department and other government services and which were available for study, were analyzed to determine their completeness, clarity, and adequacy for personnel utilizing these documents. The government documents that were analyzed include specifications and standards, supply catalogs, technical publications, training material, and miscellaneous material such as maintenance instructions, maintenance reporting, and the Coordinated Shipboard Allowance Lists for Naval Ships.

A total of 117 documents considered pertinent to the study were analyzed and are listed in Appendix E. The documents include 89 specifications or standards, 3 supply catalogs, 15 technical publications, 4 training documents, and 6 miscellaneous documents. Although some overlap in coverage by documents pervails, each of the categories was treated separately.

D. Navy Fleet Usage

The U.S. Naval Fleets, with the permission of the SHIP Type Commanders, were requested to provide information concerning the Fleet use of wire rope. Fleet responses to a questionnaire pertaining to wire rope were reviewed and analyzed to identify areas of significant problems and to provide direction for future research and development efforts in wire rope by the Navy. Analysis of the results indicates that the causes of Fleet wire rope problems are primarily attributable to the following:

1. The supply of wire rope and associated components is a major problem because of ineffective standardization, insufficiently

definitive specifications, and supply catalogs that are unresponsive to the needs of the Fleet.

2. The lack of a Fleet training program for wire rope use causes significant problems. Maintenance instructions and maintenance reporting are not effective due to a lack of training.

3. Adequate facilities and lubricants for proper maintenance of wire rope are lacking in the Fleet. Properties desired for a lubricant are high- and low-temperature resistance, core penetration, and easy applicability, and the lubricant should be aesthetically clean.

4. The choice of either wire rope or synthetic fiber rope for towing hawsers is not well established.

5. Stowage of wire rope is a problem on board ship which is only emphasized by the lack of standardization.

6. Facilities for the application of wire rope terminations are not uniform in the Fleet, and training of personnel is lacking in areas such as swaging.

7. Various types of fittings are employed and replacement is generally on an "as required" basis. Many types and sizes of fittings result in coupling difficulties.

8. No uniform criteria for wire rope replacement are contained in the Fleet responses to the questionnaire.

9. Fleet personnel are not aware of the role of wire rope in some shipboard systems (e.g., steering mechanism).

10. The Fleet response indicates insufficient standardization of wire rope sizes and constructions within the fleet.

11. Wire rope specifications are not sufficiently restrictive and the designer does not have sufficient control over material properties.

APPENDIX B

ARMY PROGRAMS ON WIRE ROPE

A. A Review of Army Programs on Wire Rope*

Wire rope finds a variety of uses in the Army, ranging from dam construction, elevators, construction equipment, towing of land vehicles, fuels handling equipment and other ship-to-shore launch items, aircraft control cables, and helicopter cargo handling systems. Many of these applications are direct counterparts of much greater civilian uses, and, in some cases, the wire rope may be only a small part of an overall system. Accordingly, the Army problems are similar to those encountered in industrial usage. These problems include inspection and retirement of wire rope, and strength of fittings. It is only in aircraft applications that Army problems associated with wire rope are formidable or unique.

Typically, wire rope used in Army construction equipment is purchased in accordance with Federal Specification RR-W-410C, Wire Rope and Strand. The wire rope generally used is Type I, Class 2, 6x19, Construction 3, IWRC, improved plow steel, preformed, right regular lay. When the equipment is in operation, strength factors and inspections are determined in accordance with SAE J-959, Lifting Crane-Wire Rope Strength Factors. One problem that has been of some concern is that wire rope creates a hazardous situation when it comes in contact with high tension wires. The feasibility of developing a non-conductive load line for cranes has been considered. It was determined that metallic wire ropes would not have the desired properties, but that polyester and polypropylene materials might be satisfactory. Even with such materials, a moisture-impervious, wear-resistant coating would be needed. Apparently, this has not been pursued further.

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*Prepared for the Committee by Dr. Eric B. Kula, Army Materials and Mechanics Research Center, Watertown, Massachusetts; March 1972.

In marine environments, the Army uses wire rope for ship-to-shore fuels handling systems, most of which is purchased in accordance with RR-W-410C. For example, the M200 Explosive Embedment Anchor uses Type IV, Class 3, Construction 2, flattened strand, 1-1/2 inch diameter, 6x30, IWRC, while the M50 Explosive Embedment Anchor uses Type I, Class 2, 1 inch diameter, 6x19, IWRC. The 8 inch Floating Hose Line System uses Type I, Class 2, improved plow steel, 1/2 and 5/8 inch diameter, galvanized, 6x19. For launching the fuel pipeline from shore to ship, a proprietary wire rope, torque balanced, extra improved plow steel, 5/8 inch diameter, 3x72, IWRC is used.

In all marine environments, corrosion is a serious problem and degrades the strength of the rope, as has been determined by tests carried out by the U.S. Army Engineer Research and Development Laboratories. Pure aluminum or aluminum -5 percent zinc anodes attached to the wire rope have been shown to decrease the amount of corrosion and diminish the strength decrease accompanying long time submerged exposure.

B. Technical Problems Relating to Use of Cable in U.S. Army Aircraft Systems*

Helicopters of the U.S. Army are commonly required to lift and transport external loads. These aircraft are fitted with cargo hoist mechanisms and cables or "tension members" to raise or lower the load which is suspended below the aircraft in flight. The tension member is equipped with an end fitting which attaches to slings supporting the load itself. Both slings and tension member pose technical problems deserving of attention.

The tension member is atypical of most cable applications in the variety of factors involved in its design. Aside from reliability and maintainability of the member itself, certain of its characteristics affect the aircraft structure, flight dynamics and, indeed, survivability of the helicopter. Thus, the tension

*Prepared for the Committee by Mr. Stuart V. Arnold, Army Materials and Mechanics Research Center, Watertown, Massachusetts; March 1972.

member must not only withstand operational load cycles, but also resist abrasion, corrosion and other environmental factors tending to degrade performance. Since some degradation does occur with continued service, the member must be amenable to inspection which will assure serviceability. Since tension members and hoist mechanisms impose a severe weight penalty on the aircraft and so limit its operational effectiveness, characteristics of the member which contribute to its own weight and that of the hoist must be considered. Thus, it is desirable to achieve a high strength/weight ratio in the member, yet retain sufficient flexibility that it can be wound around a hoist drum of modest dimensions. The member must not tend to rotate (unwind) under load, since the position of the external cargo affects the aerodynamics of the system. Elastic properties must be such as to restrict the spring-like interaction between load and aircraft. The aerodynamic profile of the member itself should avoid fluttering instability and resultant vibration. Should loss of load occur in flight, release of elastic energy within the member must not present a hazard to safety of the aircraft.

Whereas tension members could conceivably be fashioned variously as wire rope, wire rope belt, steel tape, synthetic rope, synthetic tape, chain, etc., current development of a tension member for a heavy-lift helicopter to carry 22.5 tons has focused upon wire rope and synthetic rope as the two most promising approaches to meet operational requirements within the time frame. The principal effort is proceeding at Battelle-Columbus' research facility at Long Beach, California,* and involves research and development necessary to establish the design, detail the fabrication process and acceptance specification, and recommend capable fabrication sources for production of a wire rope (cable) tension member.

Other related development has consisted of design support tests of new synthetic fibers (PRD-49 Type III and Fiber B) as bundles in various twisted and finished configurations pursuant to feasibility of rope manufacture for the tension member application.

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* Now disestablished.

Also, coating of cable wire with electroless nickel containing boron was tried as a means of enhancing resistance to abrasive wear and corrosion.

The first effort is continuing, but the two latter are completed and may be reported briefly:

1. The synthetic fibers, while providing adequate strength, could not meet the fatigue requirement. Further, exterior sleeves to provide abrasion resistance and protect against ultraviolet radiation appear necessary. Possibly, special techniques for terminal attachment would be needed.

2. The nickel-boron coating, applied on partially drawn and patented carbon steel wire, was cold reduced 89 percent to final size by normal drawing procedure. Whereas the plate adhered to the wire substrate through the drawing sequence, its continuity after drawing was inadequate to provide corrosion resistance. Reportedly, mechanical properties of the coated wire were satisfactory. Abrasion resistance of the coated wire was not cited.

The principal effort, while incomplete, has achieved notable results and also identified some technical problem areas. The project evaluated .78 inch diameter cable fashioned from drawn galvanized carbon steel, 17-7PH stainless steel, and 18-2Mn stainless steel wire against "baseline" bright carbon steel wire cable, all in 6x36 Warrington Seale, Lang Lay, Round Strand, IWRC construction. Also included was .78 inch diameter cable of drawn galvanized steel in the 36x7 construction, the strands of which were swaged prior to closing. The last appears highly successful on the basis of test results to date, having achieved a failing load of 90,100 pounds. Accordingly, demonstration hardware will be fabricated to 0.70 inch diameter as necessary to achieve the 75,000 pound capacity required. The smaller diameter will result in a weight reduction for the tension member and bring about a corresponding reduction in size and weight of the hoist mechanism.

Insofar as ability to meet specified requirements, it appears that the cable will suffice. However, while the 36x7 construction showed ample fatigue life with no observable wire breaks, attempts to determine residual strength were frustrated by failure in the socket fixture rather than in the fatigued portion of the cable. Likewise, because of persistent socket failures, it was not possible to define the mode of failure typical of the fatigued cable per se. Because current nondestructive testing methods cannot consistently detect internal breaks, let alone incipient fractures, and because improved NDT methods suitable for field usage are not presently foreseeable, it is necessary that initial wire breakage occur first in external strands in order to permit visual detection prior to complete cable failure. Such external failure has not been demonstrated in the developmental cable. The technical problem of performing non-destructive inspection under field conditions should be noted as particularly important.

It remains to be determined whether the 36x7 construction, providing 25 percent greater cross-sectional density, will pose problems in socket attachment design.

Whereas this development begs questions of cable corrosion behavior (calling instead for residual strength measurements on cable wire exposed to salt fog), it must be observed there is scant precedent for action. It is not possible to define quantitatively the cumulative effect of the various microenvironments existing within the cables during service; a procedure for duplicating these within the laboratory is lacking; and construction of cable test facilities, once conceived, would prove complex and costly. It seems evident that wear, lubrication and corrosion are closely interrelated and play important roles in strength degradation and life determination. Considering cost of the tension member and the serious consequences in event of its failure, this technical problem area demands further materials research and development of test methodology.

Slings for lifting and transporting suspended cargoes are subject to many of the problems discussed above with relation to the tension member. However, elasticity and aerodynamics are of less consequence so that nylon strapping has been employed extensively. However, nylon slings have proven very troublesome because strength degradation from abrasion and ultraviolet radiation shortens life unpredictably depending on exposure, and much loss by dropped cargoes is reported. Whereas nondestructive techniques for measuring strength and predicting residual life are sorely needed, research towards materials solutions should continue. It is reported that (1) stainless steel wire cable and (2) double braided nylon rope within a colored polyeurethane sheath are presently undergoing comparative evaluation for this application. Although nylon tapes and ropes are more popular with using personnel for reasons of easy handling and storage, the wire cable slings offer promise of longer life and greater reliability (consistent with visual inspectability).

APPENDIX C

AIR FORCE PROGRAMS ON WIRE ROPE*

In its Civil Engineering functions, the USAF is a user of wire rope in the more conventional applications such as cable slings, guy wires, drags, highway or road guard rails, fire trucks and ground rescue equipment, elevator rope and the like. For most of these uses, wire rope larger than 1/4 inch in diameter is used and is procured to Federal Specification RR-W-410C "Wire Rope and Strand." There are no identifiable serious problems with the use of these ropes in such applications. Replacement schedules are based on conventional visual inspection techniques (Bethlehem Steel Corporation), and are consistent with the industry's recommendations in this regard.

In a more demanding role, the USAF is an extensive user of the larger diameter 1-1/4 inch rope for arresting aircraft threatened with over-running the end of the runway. The extensive development work and experience of the Navy in cable arrestment of aircraft is taken advantage of in this application and all procurement is made in accordance with the U. S. Navy developed specification (NAEC Misc. No. 08787, 17 Feb 1969) for this rope. Problems encountered with the use of aircraft arresting systems have been largely with components other than the wire rope. Rope replacement schedules are based on visual evidence of excessive wear or wire breakage ("excessive" not precisely defined) or at 18 month intervals, whichever comes first. This is the presently recommended practice whether or not there have actually been any aircraft engagements during the 18 month interval. It reflects a concern for deterioration effects which cannot be confidently determined by non-destructive means.

A third use for wire rope in the U. S. Air Force is for aerial gunnery target towing. The users indicate satisfactory service is being obtained from

*Prepared for the Committee by Mr. Walter P. Conrardy, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio; March 1972.

currently available rope which is procured to U.S. Navy prepared specifications (Military Specifications MIL-C-5765D(1) and MIL-C-22282) for this product.

A fourth use for this product is in helicopter rescue hoist cable. Our principal rescue helicopter, the HH-3 or "Jolly Green Giant," has a heavy duty, large diameter reel drum that has been designed for many cycles of hoisting and no unusual wire rope problems have been disclosed with this system. On the other hand, we have encountered wire rope failures when using the UH-1N helicopter in training exercises "rescuing" downed airmen from the Gulf of Mexico. The hoist system in this vehicle was designed as an emergency rescue hoist system (50 cycles would be a reasonable number of lifts before cable replacement) and not designed for continuous use. The reel is small diameter because of space constraints and the wire rope experiences severe reverse bending in this application. As a result, when used in a training environment requiring continuous use of the hoist, extremely short lives have been experienced.

The cable used is similar to that used for aircraft control cable (MIL-W-83343) and the data base and service experience is related to stresses encountered in control cable use. This is typically in the 50 pounds load range. In rescue work, a fully dressed, soaking wet aviator is in the 200-plus pounds range, which results in a severely shortened fatigue life. To determine a safe replacement schedule, the Aeronautical Systems Division has conducted service life tests at Wright-Patterson Air Force Base using a UH-1N installation and loads varying from 200 to 600 pounds. (Specification minimum breaking strength is 3330 pounds.) A safety factor will then be applied to account for scatter, environmental (corrosion) problems, etc., and replacement schedules rigidly adhered to in order to prevent future accidents so long as this hoist system continues in this type of service.

A common U.S. Air Force application, of course, is in general aircraft control cable use, (MIL-W-83343). The U.S. Air Force is switching over to nylon jacketed cable almost exclusively. This keeps the lubricant in, dirt and environment out and provides some protection against crushing and abrasion.

Our experience thus far, since its introduction in 1966, has really been outstanding. Of some 10,000 individual nylon jacketed SS cables in service, only one has been replaced and that was for precautionary reasons only. A section of the nylon jacket had been heat damaged so the cable was replaced. In prior use of the unjacketed cable, there are some applications, for example in the T-38 aircraft, where a very small diameter sheave is used, where replacement at 50 hour flight intervals was required. Since introduction of the jacketed cable, no replacement at all has been required and the engineers responsible for this hardware anticipate lifetime (of the aircraft) usage.

Commercial aircraft experience was also cited since these aircraft accumulate much more flight time than military aircraft. Continental Airlines, for example, is replacing nylon jacketed cables only at 12,000 flight hour intervals, at which time the aircraft gets a very extensive tear-down inspection and overhaul. Cables being removed look essentially undamaged but are being replaced at this interval since it is common practice in the aircraft business not to put old cables, once removed, back into service.

Within the U.S. Air Force, periodic inspection of aircraft cables is done "in-place" on the aircraft. It is accomplished by passing a cloth gloved hand down the cable, feeling for broken wires. Two broken wire ends per inch of cable would be cause for replacement. There are no other nondestructive inspection (NDI) techniques currently specified for inspection of these cables.

A final and unusual application of wire rope that represents a current U.S. Air Force problem is related to the Low Frequency Trailing Wire Antenna system used on the Airborne Command Post. The SAC operated EC-135 (and eventually the EC-747) uses a long length trailing wire anntenna system for low frequency radio communications with its various strike units and headquarters areas. Because of the length of wire needed (28,000 to 40,000 feet), diameter, and volume constraints, low resistivity electrical requirements, etc., this presents a unique utilization of high strength wire rope construction.

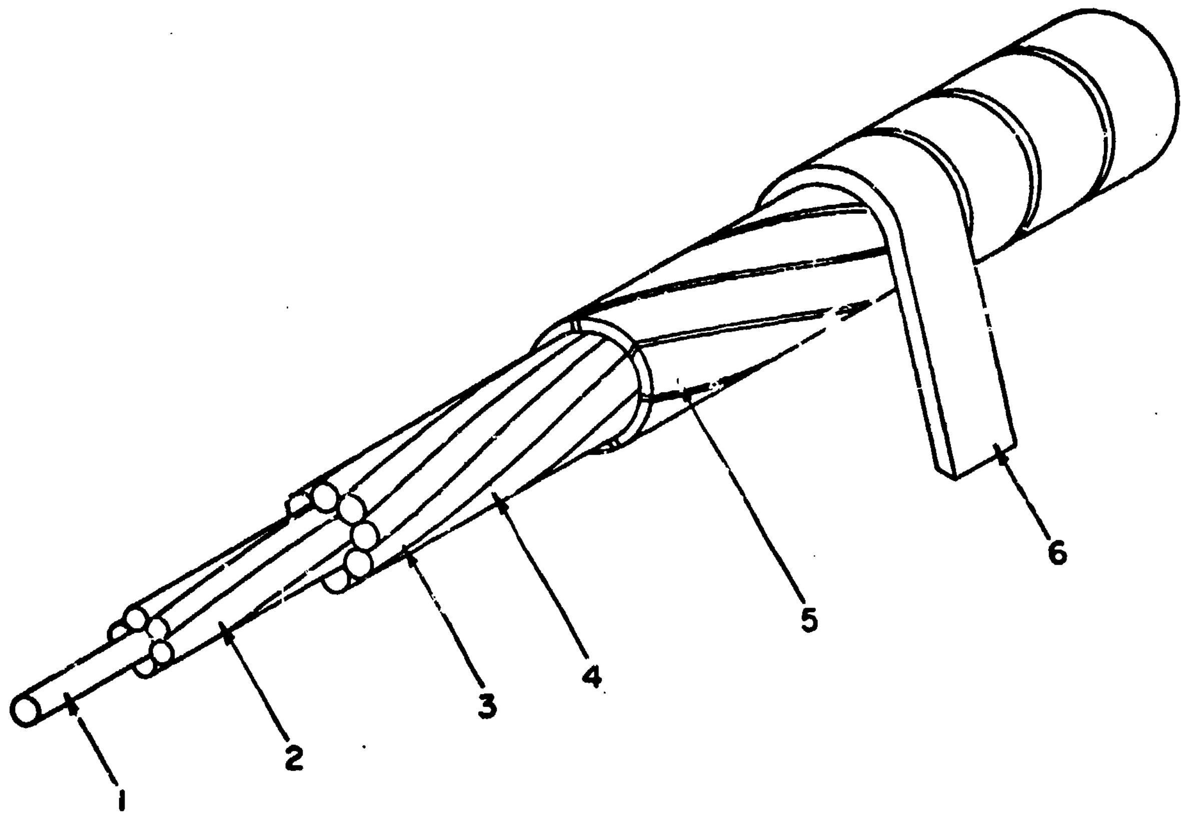
The general approach has been to use a 1x19 Warrington steel wire rope construction, overwrapped with copper strip to yield the surface electrical characteristics needed, about 4 ohms per 1000 feet of length at a frequency of 17 KHz. (See Figure 5.)

In 1967, the material being used was described as carbon steel rocket wire (CSRW) with a breaking strength of the "rope" of 2780 pounds. The general goal for improvement was to increase the breaking strength by 25 percent and to double the fatigue life. At that time, the American Chain and Cable Co. was the rope supplier to a Collins specification (Richardson, Texas).

The antenna uses an aluminum cone drogue at the end for wire stabilization. At speeds and altitude flown, drags experienced are high and the wire flies nearly horizontally behind the towing aircraft. The drag results in high tensile loads on the wire and most failures are considered to be tensile overloads. The wire rope was constructed of .018 inch (425,000 psi), .023 inch (400,000 psi), and .024 inch (395,000 psi) steel wire. Outer wraps of copper are overlaid to yield the low resistivity surface. This is, of course, critical to electrical efficiency of the antenna.

Because of the dimensional constraints on the reeling unit (OA-8035/ARC-96 Trailing Wire Antenna System), the cable or wire rope goal for the outside diameter (O. D.) is a maximum of .160 inch. Fifty extend-retract cycles is also a goal. We are presently getting only 10 to 12 cycles.

In the laboratory evaluation of wire rope constructions (Figure 6), by cycling over sheaves under simulated tension loads, an increase in the diameter of the cable of .004 inch constitutes a failure. The starting diameter is .160 inch and maximum that the reel can handle is .164 inch, where troubles begin. This diameter increase signals the yielding and separation of the copper wrap layers which also greatly increases the electrical resistance and reduces the antenna efficiency.



No.	Wire Size	Type of Wire	Lay Length
1	0.024	U.H.S.	Straight
2	0.023	U.H.S.	1
3	0.018	U.H.S.	1
4	0.024	U.H.S.	1
5	0.018 × 0.053	Copper-clad	$1\frac{1}{2}$
6	0.017 × 0.125	Copper	$\frac{5}{32}$

A-57297

FIGURE 5. ACCO Cable Design – 1 x 19 Warrington (Gilmore and Mesler, 1973)

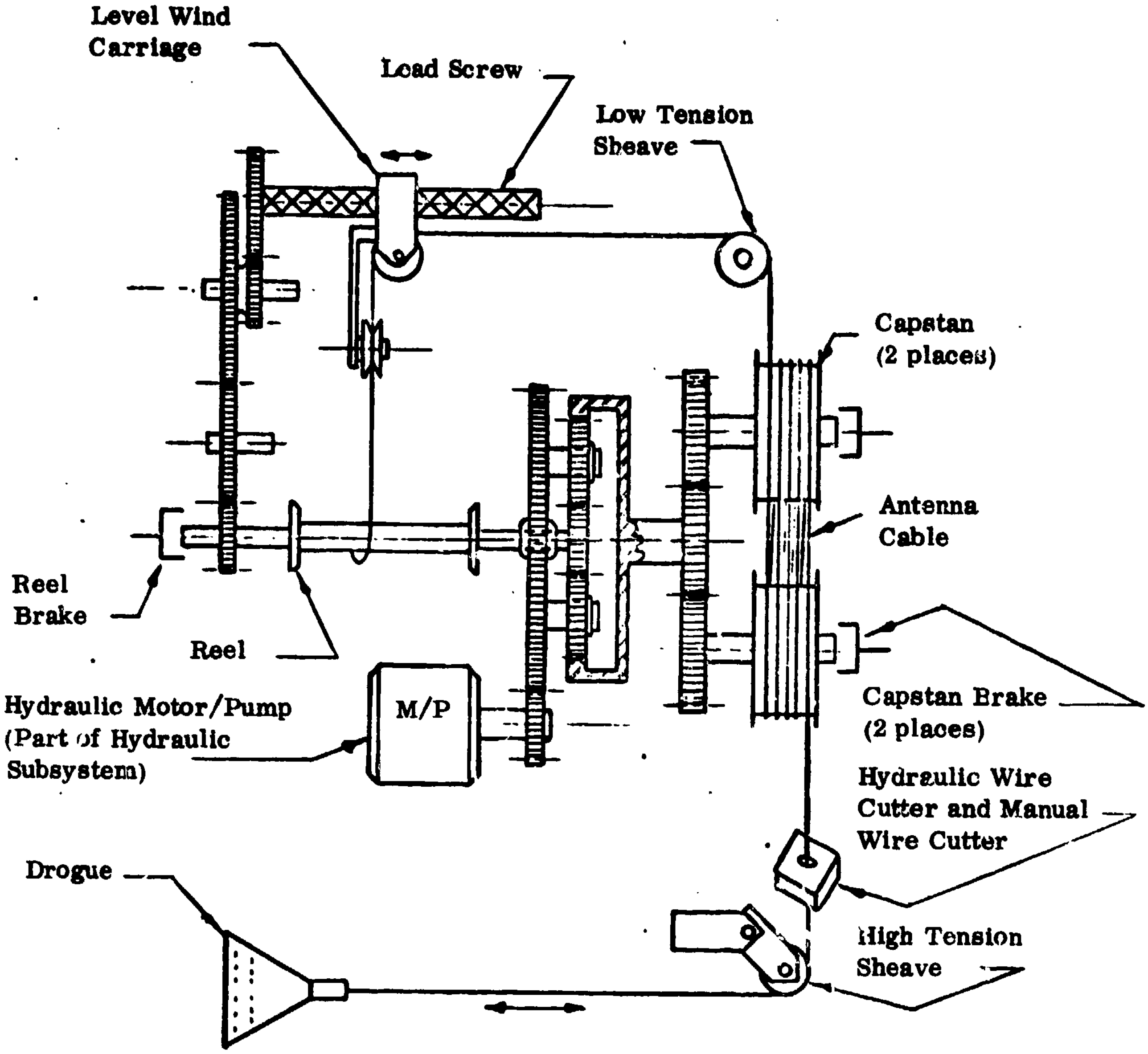


FIGURE 6. Mechanical Subsystem, Simplified Diagram.

Some redesign work has gone into the reel and wire. The new reel prototype now includes a die to squeeze the copper cladding back onto the wire rope as it is reeled back into the aircraft. Some extension of life, in lab tests, has been demonstrated by this technique and will be flight tested together with the Battelle-developed new wire constructions. Higher mechanical strength has been demonstrated, about 4000 pounds versus 2780 pounds for present constructions. Reportedly the electrical properties have also been maintained.

A new study effort recently has been conducted for the design, construction, and testing of a tapered wire rope. In a trailing antenna, the highest tensile loads are at the aircraft (reel) end and lowest at the drogue; thus, maximum strength is needed only at aircraft end and a constant diameter cable, though easier to make, results in weight and volume problems, and because of weight, (higher tensile loads) shorter lives. An alternative way of obtaining a low resistivity surface is to use an overwrap strip of laminated copper on a steel substrate. Also being considered is copper plated wire construction. The take-up reel for such a concept introduces additional complexities. The concept has not been prototyped or tested yet.

Thus, it can be concluded that:

1. USAF problems with conventional applications of wire rope and cable are not as severe as those experienced in Naval applications.

2. The USAF does have a serious short-life problem with high strength, small diameter wire rope antenna cable, however, a development program to extend life in this application is being pursued.

3. The lack of a reliable NDI method for inspecting all forms of cable forces conservative replacement practices that undoubtedly raise overall operating costs.

To remedy this situation, additional emphasis should be placed on developing a reliable NDI technique, usable in the field.

References

Bethlehem Steel Corp., 1427168, "Inspection of Rope in Service," 00A0395 0-00-00.

Gilmore, W. J., and Mesler, W. L. "Flat Wire Structure and Apparatus and Method of Making Same." U.S. Patent No. 3,717,987 (American Chain and Cable Company, Adrian, Michigan), February 27, 1973.

Hackensack Cable Corp., Report to the Aircraft Industry, "Recommended Pulley Dimensions."

AFSC DH 2-1 Section 3B, "Flight Control Systems."

AFSC DH 2-1 Section 5C, "Aerial Towing."

Federal Specification RR-W-410C, "Wire Rope and Strand."

MIL-C-22282, "Cable, Tow Target, Steel."

MIL-C-5765D(1), "Cable, Tow Target, Armored Steel."

MIL-C-83140, "Wire Rope, Steel (Stainless Steel) Preformed, Nonrotating, for Aircraft Rescue Hoist and Cargo Handling."

MIL-W-83343, "Wire Rope Steel (Corrosion Resisting) Nylon Coated."

NAEC Misc. No. 08787, "Wire Rope, Steel 1-¼ Inch Diameter (12x6)/(6x30) Non-Rotating, Polypropylene Core, High Strength (for Aircraft Arresting)," 17 February 1969.

APPENDIX D

WIRE ROPE IN THE MINING INDUSTRY*

The uses of wire ropes in the mining industry can be divided into two categories, critical (or fail-safe) applications, such as ropes for hoisting shaft cars and aerial tramways, and less critical applications, such as ropes for slushers, draglines, and shovels. Hoist ropes that are used to convey men simply cannot be permitted to fail and their selection, usage, inspection, and retirement are controlled more or less rigidly by federal and state regulations. Good engineering practice and, to a lesser extent, legal codes also tend to encourage frequent inspection and lubrication of other ropes and to require their replacement before failure. In general, it can be said that the usage of wire rope in the mining industry has become standardized and that this standard "good engineering practice" has been codified and required by federal and state regulations. When a novel problem appears, the mining engineer generally relies upon the rope manufacturer's engineering staff for help in solving the problem. If the solution is acceptable and the new practice is adopted by other mining or equipment companies, the state and federal regulations eventually catch up and ossify the procedure.

A. Selection of Wire Ropes for Duty in Mines

It can be said that the vast majority of hoist ropes used in mining are selected primarily by static safety factors. Other considerations, of course, enter into the selection process, such as style of construction as it influences flexibility, crushing and abrasion resistance, and wire rope material (extra improved plow steel versus improved plow steel, etc.); however, the static safety factors are specified in detail in most state codes and the engineer has no choice but to abide by these regulations. The usual table of safety factors is given below:

* Prepared for the Committee by Dr. Earl R. Hoskins, Professor of Mining Technology, South Dakota School of Mines and Technology, Rapid City, South Dakota; March 1972.

Shaft Depth (in feet)	Static Safety Factors	
	New Rope	At Discard
< 500	8	6.4
500-1,000	7	5.8
1,000-2,000	6	5.0
2,000-3,000	5	4.3
> 3,000	4	3.6

This table has been taken from American National Standards Institute Specification M 11.1 - 1960 on Wire Ropes for Mines. According to this specification, rope acceleration should be limited to 6 ft/sec/sec and minimum and recommended sheave-to-rope diameter ratios for various rope constructions are given in another table. Unfortunately, many of the committees preparing state codes apparently did not read beyond the table of static safety factors when they plagiarized the hoisting rope provisions from M 11.1 - 1960 (or in a few cases, M 11 - 1927) and no restrictions are placed on rope acceleration and few on sheave-to-rope diameter ratios. A few states (e.g., New Mexico) specify that "the load due to the acceleration of the dead load and load-caused friction should be added to the dead load" when calculating the safety factor.

None of the state codes studied specify any means of calculating stresses due to the bending of a rope over various size sheaves. This is probably just as well, as none of the various formulae that have been proposed for calculating bending stresses are considered reliable. However, if sheave-to-rope diameter ratios are not specified and no allowance is made for bending stresses, the safety code has simply not recognized the problem. Minimum sheave- or drum-to-rope diameter ratios required in Canada are generally higher than those required in the U.S., and still higher ratios are specified in European countries.

Ropes used for slushers, shovels, draglines, dredges, etc., are usually chosen for their abrasion, crushing, and kinking resistance. These ropes are subject to considerable abuse and random shock loadings. They are picked by the operators or equipment manufacturers based on their field experience and the strength of the rope bears little relationship to the static or calculable loads expected. The ropes are used nearly to destruction, and maintenance and lubrication are much less well controlled than is the case with mine hoist ropes.

B. Inspection of Mining Ropes

Hoist ropes are inspected at least once a day visually for broken surface wires or other obvious deterioration. At regular intervals, usually six months, most state codes require that six feet of the hoist rope be cut off the end fastened to the conveyance and discarded. In addition, some states require that the rope be moved ahead on the drum periodically in order to change the position of the crossover points where wrapping onto the drum. Further, it is occasionally required that the rope be "end-for-ended" at six-month intervals. It is usually stated that the rope should be periodically calipered, and in a few states that the rope should be discarded when two years old unless approved for further use by the state inspector.

In the U.S., no state requires nondestructive testing (NDT) of hoist ropes, and several specifically say that NDT is to be used only as a supplement to visual inspections and not as a replacement for them. Most of the Canadian provinces encourage the use of NDT, and Ontario requires it.

All rope inspections are recorded in an official rope record or log book which is kept for each individual piece of rope. This rope log is available at all times to federal or state inspectors.

C. Retirement of Rope

Retirement of mine hoist rope in the U.S. is based on visual inspection, age, and tons or ton-miles of hoisting duty. The more stringent of the various state codes usually require changing a rope if it is kinked, has six visible broken wire per lay length, has 35 percent or more wear in the crown wires, marked corrosion occurs, or if the static safety factor drops below the minimum value set in M 11.1 - 1960. Only a few states specify that a length of rope be cut off periodically and tested to determine its actual strength at any time.

The Canadian requirements are in general more stringent. Electromagnetic testing to determine internal corrosion is either encouraged or required; if the residual "strength" of the rope drops to 90 percent of the original strength (as it was determined by actual test) the rope must be discarded. Criteria for replacing ropes based on visual inspections are as strict or stricter than the most stringent U.S. state requirements.

APPENDIX E

LIST OF GOVERNMENT WIRE ROPE DOCUMENTS

Specifications

General Specification for Ships

Section 9120-1	**Mooring and Towing Fittings**
Section 9120-2	**Rails, Stanchions and Life Lines**
Section 9170-1	**Masts and Spars**
Section 9180-1	**Rigging and Canvas**
Section 9200-3	**Cargo Handling and Replenishment at Sea**
Section 9250-1	**Towing Machines**
Section S82-1	**Boats and Life Floats — Stowing and Handling**
Section S83-1	**Aircraft Stowage, Handling, Landing and Launching Facilities**

Federal Specifications

RR-G-691A	Grip, Cable, Jaw
RR-G-700B	Rope, Wire
RR-S-550	Sockets, Wire Rope
RR-S-00750	Strands, Steel Wire, Zinc Coated
RR-W-00420A	(GSA-FSS) — Wire Rope, Steel (Highway Guard)
RR-W-410C	Wire Rope and Strand
QQ-B-750	Bronze, Phosphor; Bar, Plate, Rod, Sheet, Flat Wire, and Structural and Special Shaped Sections
QQ-W-423E	Wire, Steel, Corrosion-Resisting
VV-L-751C	Lubricating Oil: Chain, Wire Rope and Exposed-Gear
GGG-V-436D	Vises
GGG-V-412A	Vise, Hand, Pin, Wire Rope Splicing, and Square End Sawing, Tube

Military Specifications

MIL-B-24141 (SHIPS)	Blocks, Tackle, Wire Rope
MIL-C-5424A	Cable: Steel (Corrosion-Resisting) Flexible, Preformed (for Aeronautical Use)
MIL-C-5688A	Cable Assemblies: Aircraft Proof Testing and Prestretching of
MIL-C-5693C	Wire Strand, Steel (Corrosion-Resistant) Preformed (Aircraft Application)
MIL-C-5765D	Cable, Tow Target, Armored Steel
MIL-C-11796B	Corrosion Prevention Compound Petrolatum Hot Application
MIL-C-11850C	Cable Assemblies, Camouflage Net Release, Wire Rope, 1/8 Inch Diameter
MIL-C-16173D	Corrosion Preventative Compound, Solvent Cutback, Cold Application
MIL-C-18375A (ASG)	Cable: Steel (Corrosion-Resisting, Non-Magnetic) Flexible Preformed (for Aeronautical Use)
MIL-C-22283 (WEP)	Cable, Tow Target, Steel
MIL-F-17280C (SHIPS)	Fittings, Marine, Minesweeping, Nonmagnetic
MIL-F-52553 (ME)	Fittings, Wire Rope
MIL-G-160A	Grips, Cable (Naval Shipboard Use)
MIL-G-3210A	Grip, Cable, Jaw
MIL-G-12434A (CE)	Grips, Cable, Jaw, Wedge and Roller Type
MIL-G-16567A (SHIPS)	Grip, Cable
MIL-G-18458A (SHIPS)	Grease Wire Rope — Exposed Gear
MIL-H-794	Holder, Cable Splicing
MIL-H-19925B (YD)	Hoists, Wire Rope, Electric Powered
MIL-L-22803 (WEP)	Lubricant, Wire Rope
MIL-P-24216A (SHIPS)	Polypropylene Cores, Strand Centers and Substrands for Wire Rope
MIL-R-2878B	Rope, Wire, Steel (Carbon) High Strength, Galvanized (for Target Towing Hawsers)
MIL-R-7871 (AER)	Rope; Extra-High-Strength Wire, 6 x 19 with 7 x 7 Independent Wire Rope Center (for Aircraft Launching and Arresting)

MIL-R-8492B	Cable Grip, Rescue Equipment Helicopter
MIL-R-15716 (BUORD)	Rope; 18 x 7 Non-Rotating Hoisting Wire
MIL-R-20089	Rope, Wire, Mine Sweeping
MIL-S-16212A (NORD)	Strand, Steel Wire, Zinc-Coated (for Nets)
MIL-S-21433A (SHIPS)	Sockets, Turnbuckles, and Turnbuckle Assemblies. Wire Rope, Wedge, and Threaded Lock Sleeve.
MIL-S-22824A (NAVY)	Slings, Multiple Leg, Vehicle (Shipboard Loading)
MIL-T-781B	Terminal; Wire Rope Swaging
MIL-T-6117B	Terminal — Cable Assemblies, Swaged Type
MIL-W-1511A	Wire Rope, Steel (Carbon) Flexible, Preformed
MIL-W-2176A	Wire Rope, Steel, Spring Lay (Alternate Fiber Strands and Steel Wire Strands around a Fiber Center)
MIL-W-2902C (SHIPS)	Wire Rope Assemblies, Single Leg, Oxygen Breathing Apparatus Safety Lines
MIL-W-3093C	Wire Rope Assemblies, Single Leg (Sling Type)
MIL-W-5424B	Wire Rope, Steel (Corrosion-Resisting) Flexible, Preformed (for Aeronautical Use)
MIL-W-5693C	Wire Strand, Steel (Corrosion-Resistant) Preformed (Aircraft Applications)
MIL-W-6015A (ASG)	Wire Rope, 6 x 19, High-Strength (for Aircraft Launching and Arresting)
MIL-W-6940B	Wire Strand, Steel, Nonflexible (Preformed)
MIL-W-8957A (ASG)	Wire, Steel, Carbon, High Strength
MIL-W-8958 (ASG)	Wire, Steel, Corrosion-Resistant, High Strength (AM 355)
MIL-W-10700B	Wire Rope and Wire Rope Fittings, Packaging of
MIL-W-12567C	Wire Strand, Steel (Wires WS-3/u, WS-4/u, W-90, W-115 and W-116)
MIL-W-18242A (SHIPS)	Wire Rope and Wire Rope Assemblies; Single-Leg, Corrosion-Resisting Steel Minesweeping
MIL-W-19460B (SHIPS)	Wire Rope Assemblies, Single Leg, Grapnel and Buoy Type

MIL-W-21632 (SHIPS)	Wire Ropes, Steel, Bare and Nylon Covered, Corrosion-Resisting, Flexible, Preformed, Oceanographic and Bathy-Thermographic
MIL-W-21993A (OS)	Wire Rope Assembly, Mooring, Mark 1 Mod 1
MIL-W-23116 (WEP)	Wire Rope, Steel, Fiber Core, 6x25, High-Strength (for Aircraft Arresting)
MIL-W-23711 (WEP)	Wire, Steel, Carbon, High Strength
MIL-W-24223	Wire Rope, Aluminized
MIL-W-52312 (MO)	Wire Rope Assemblies, Single Leg; for Medium Cableway
MIL-W-81002 (WP)	Wire Rope, Steel, 1-3/8 inch Diameter, 6x30, Type G, Lang Lay Flattened Strand Fiber Core, High-Strength (for Aircraft Arresting)
MIL-W-81178 (WP)	Wire, Rope, Steel, 1-3/8 inch Diameter, 6x25 Filler Wire, Fiber Core, Lang Lay Round Strand, High-Strength (for Aircraft Arresting)
MIL-W-83140	Wire Rope: Steel (Stainless Steel) Preformed, Nonrotating for Aircraft Rescue Hoist and Cargo Handling (Winching)

<u>Military Standards</u>

MS-163B	Steel Mill Products Preparation for Shipment and Storage
MS-17339 (SHIPS)	Cable, Safety (Wire Rope)
MS-17351 (SHIPS)	Wire Rope Assembly, Single Leg
MS-17352 (SHIPS)	Terminal, Wire Rope, Swage Type
MS-17353 (SHIPS)	Wire Rope, Steel, Flexible
MS-20658	Terminal, Wire Rope Swaging, Fork End
MS-20667	Terminal, Wire Rope, Swaging, Fork End
MS-20668	Terminal, Wire Rope, Swaging, Eye End
MS-21259	Terminal, Wire Rope, Stud
MS-21260	Terminal, Wire Rope, Stud
MS-90382	Grip, Cable, Rescue
MS-90561	Grip, Cable, Woven, Strain Relief, Axial

Simplified Practice Recommendation

SPR-139-50	Wire Rope

NAVSHIPS Design Data Sheet

DDS-1702-1	Stayed Pole Mast

Airforce-Navy Aeronautical Design Standard

AND-10081	Terminal Shank-Swaging, Dimensions for

Supply Documents

Illustrated Shipboard Shopping Guide

Federal Supply Catalog — Navy Edition

Naval Stock List of General Stores (obsolete)

Technical Bulletins and Manuals

NAVSHIPS Technical Manual

Chapter 9170	Cranes and Booms
Chapter 9180	Rigging
Chapter 9200	Winches and Capstans
Chapter 9220	Steering Gear
Chapter 9250	Towing Gear
Chapter 9260	Mooring and Appliances
Chapter 9270	Wire Rope
Chapter 9320	Boats and Lifesaving Craft
Chapter 9830	Elevators

NAVSHIPS Technical Bulletin No. 5

NAVSHIPS 250-008-5	Instructions for the Design and Care of Wire Rope Installations

U. S. Navy Ship Salvage Manual, Vol. 1

NAVSHIPS 0994-000-3010	Theory of Strandings and the Use of Beach Gear

Roebling Wire Rope Handbook, U. S. Navy Edition

NAVSHIPS 0900-008-9010

Conventional Weapons Manual — SUBLANT Force Instruction 08000

15 Art 9012	Inspection Criteria for Wire Rope

Operational Transfer Procedures Handbook

FAST NAVSHIPS 0920-025-1020

FAST NAVSHIPS 0920-025-1030

Miscellaneous

Navy Training Course

NAVPERS 10121-D	Boatswain's 3 and 2
NAVPERS 10122-C	Boatswain's 1 and C

Preventive Maintenance System (PMS)

Coordinated Shipboard Allowance Lists for Naval Ships

<u>Navy Training Films</u>

MN-2340A	Shipbuilding Skills — Rigging — Use and Care of Wire Rope
MN-2340G	Shipbuilding Skills — Wire Rope Terminal Connections — Parts 1 and 2

APPENDIX F

A SURVEY OF ROPE TESTING

A letter survey was carried out by sending a formal questionnaire to 30 organizations concerned with the testing of rope. Both manufacturing and research establishments. were included. The following 12 organizations responded:

Dr. Ing. H. Arnold
Westphalian Office of Mining Inspection
463 Bochum, Dinnendahlstr. 9
Germany

Mr. A. F. Beighley
Bethlehem Steel Corporation
Williamsport, Pennsylvania 17701

Mr. G. R. Borwick
National Engineering Laboratory
East Kilbride, Glasgow
Scotland

Mr. F. Canfield
Leschen Wire Rope Company
Wire Rope Corporation of America
606 N. 2nd Street
St. Joseph, Missouri

Mr. F. Chiapetta
MacWhite Wire Rope Company
2906 - 14th Avenue
Kenosha, Wisconsin 53140

Mr. H. A. Cress
Battelle Laboratories
Long Beach, California

Mr. R. A. Cruess
The Twining Laboratories, Inc.
2527 Fresno Street
Fresno, California 93716

Mr. D. Healey
Admiralty Materials Laboratory
Holton Heath
Poole, Dorsey
England

Prof. Dr. Ing. H. Mueller
Research Institute for Transportation Technology
Stuttgart University
1, Holzgartenstr., Stuttgart 1
Germany

Mr. H. T. Plant
British Ropes Ltd.
Carr Hill, Doncaster
England

Prof. Ugo Rosetti
International Organization for the Study of
Cable Endurance
Politecnico, 10100 Torino
Italy

Mr. G. E. Winder
Safety in Mines Research Establishment
Broad Lane, Sheffield
England

A summary of the responses is given in the Questionnaire (Table 2) and the Summary of Responses to Questions on Testing Capabilities (Table 3). Less than half of the responding organizations considered the existing data inadequate or recommended the collection of more data or information.

TABLE 2. Questionnaire with Summarized Responses.

Scope

1. What is the principal field of application of wire rope with which you are concerned? General: 6 Testing: 2 Mining: 2
2. Do you test/study wire rope for:
   a. Manufacturers Yes: 6 No: 3
   b. Designers of equipment using wire rope Yes: 5 No: 5
   c. Users of Wire Rope Yes: 10
3. Do you carry out:
   a. Routine tests on wire rope Yes: 9
   b. Development of wire rope Yes: 8
   c. Support studies of development programs of wire rope Yes: 4
   d. Failure analysis Yes: 10
   e. Stress analysis of wire rope systems Yes: 7
4. Do you test/develop/study:
   a. Rope sheaves Yes: 5
   b. Rope attachments Yes: 8
5. Do you test/develop/use non-destructive test equipment on wire rope Yes: 6 No: 4

Test Equipment Capabilities

1. Tensile testing:
   a. Maximum rope length ______
   b. Maximum test load ______
   c. Range of test speeds ______

   See Table 3
2. Dynamic testing (fatigue):
   a. Length of specimen ______
   b. Maximum number of test direction reversals ______
   c. Range of sheave diameters ______

   See Table 3

TABLE 2. Questionnaire with Summarized Responses (continued).

Test Equipment Capabilities (continued)

2. Dynamic testing (fatigue) (continued)

   d. Load Range
   e. Range of rope diameters
   f. Range of linear rope speeds
   g. Rate of load reversal

   See Table 3

3. Environmental testing:

   a. Controllable temperature range Yes: 3
   b. Humidity environment range Yes: 4
   c. Chemically active environments (e.g., salt) Yes: 5
   d. Do you test environment effects statically (tensile test) or dynamically?
      Statically: 3 Dynamically: 3

4. Special equipment:

   a. Wire rope Tensile: 1 (creep tester) Torsion: 1 Fatigue: 6
   b. Wire rope core — what tests?
      Rope fatigue: 1 Corrosion: 1 Stiffness: 1
   c. Wire rope lubricants — what tests? Rope fatigue: 2 Corrosion: 2

5. Non-destructive test equipment:

   a. What methods have you investigated? Electro-magnetic: 1
      Magneto-indictive: 1 Eddy current: 1 Magnetic: 3
   b. Are available instruments adequate? Yes: 3 No: 4
   c. Can you determine the following non-destructively, and by what methods:
      (1) External wire breaks Yes: 4 (methods as above) No: 1
      (2) Internal wire breaks Yes: 4 (methods as above) No: 1
      (3) Core damage Yes: 3 (methods as above) No: 2

TABLE 2. Questionnaire with Summarized Responses (continued).

<u>Information</u>

1. Do you consider present information adequate for:

   a. Optimum rope usage Yes: 3 No: 4

   b. Optimum rope design Yes: 4 No: 3

   c. Optimum design of wire rope systems Yes: 2 No: 3

2. What information not yet available would be most useful for your purposes:

   a. Rope property data Yes: 5

   b. Rope stress analysis Yes: 3

   c. Environmental data Yes: 4

   d. Nondestructive test methods Yes: 5

<u>Comments and Suggestions</u>

The following were listed as areas of interest:

a. More dynamic analysis

b. Nondestructive testing for locked coil rope

c. More fatigue data

TABLE 3. Summary of Questionnaire Responses on Testing Capabilities (questions 1 and 2).

Question	Respondent 1/	2/	3/	4/	5/	6/	7/	8/	9/	10/
Test Equipment Capabilities										
1. Tensile Testing										
a. Max. Rope Length (meters)	10	10	52	5	8	5	1.3	3	7	15
b. Max. Test Load (tons)	250	1,000	200	200	1,250	60	150	400	375	45
c. Test Speed (meters/min.)	15	.18	--	--	1,200	.2	.3	.05	.07	--
2. Dynamic Testing (fatigue)										
a. Rope Length (meters)	16	17.4	4.2	.8	8	12	--	--	--	--
b. Max. No. Test Direction Reversals	--	--	--	--	--	--	--	--	--	--
c. Sheave Diameters (meters)	0.2/3	2	.30	.18	.2/.6	--	--	--	--	.1/.3
d. Load (tons)	50	250	50	4	1,250	7.5	--	--	--	70
e. Rope Diameter (meters)	60	112	50	19	250	15	--	--	--	--
f. Linear Rope Speed (meters/sec.)	2	2	--	--	--	--	--	--	--	--
g. Reversal Rate	1	2	--	.5	--	--	--	--	--	--

1/ Research Institute for Transportation Technology
2/ Westphalian Office of Mining Inspecuion
3/ Safety in Mines Research Establishment
4/ British Ropes Ltd.
5/ National Engineering Laboratory
6/ MacWhite Wire Rope Company
7/ The Twining Laboratories, Inc.
8/ Leschen Wire Rope Company
9/ Bethlehem Steel Corporation
10/ Battelle Laboratories (Long Beach)